Mars, the Nearest Habitable World –
A Comprehensive Program for Future Mars Exploration

Report by the NASA Mars Architecture Strategy Working Group (MASWG)

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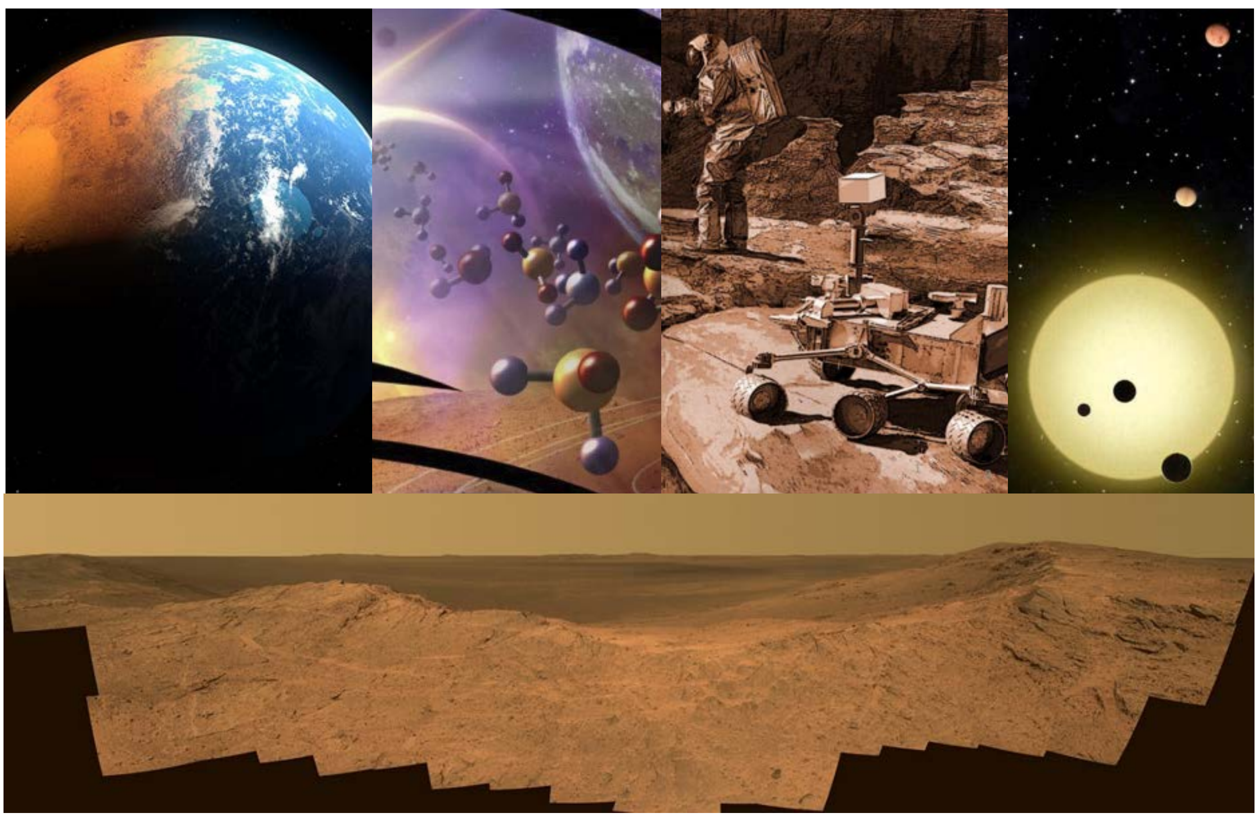

Front Cover: Artist Concepts

Top (Artist concepts, left to right): Early Mars[1]; Molecules in Space[2]; Astronaut and Rover on Mars[1]; Exo-Planet System[1].

Bottom: Pillinger Point, Endeavour Crater, as imaged by the *Opportunity* rover[1].

Credits: [1]NASA; [2]Discovery Magazine

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MASWG Members

- Bruce Jakosky, University of Colorado (chair)
- Richard Zurek, Mars Program Office, JPL (co-chair)
- Shane Byrne, University of Arizona
- Wendy Calvin, University of Nevada, Reno
- Shannon Curry, University of California, Berkeley
- Bethany Ehlmann, California Institute of Technology
- Jennifer Eigenbrode, NASA/Goddard Space Flight Center
- Tori Hoehler, NASA/Ames Research Center
- Briony Horgan, Purdue University
- Scott Hubbard, Stanford University
- Tom McCollom, University of Colorado
- John Mustard, Brown University
- Nathaniel Putzig, Planetary Science Institute
- Michelle Rucker, NASA/JSC
- Michael Wolff, Space Science Institute
- Robin Wordsworth, Harvard University

Ex Officio

- Michael Meyer, NASA Headquarters

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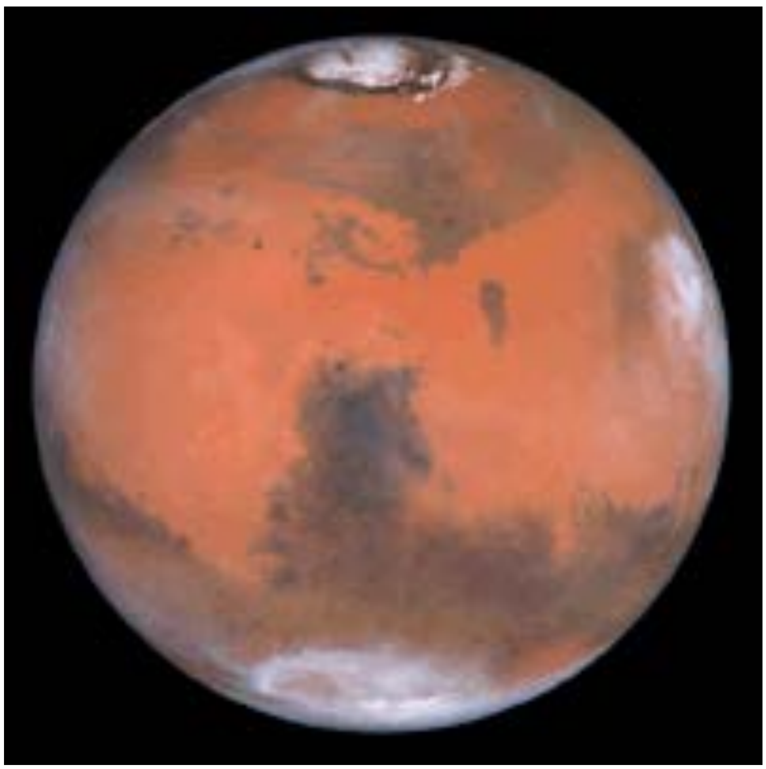


Hubble Space Telescope image of Mars, obtained in 1999. The bright and dark areas on Mars are visible, along with the summertime north polar cap at the top of the image. Water ice clouds are visible and most prominent over the south pole and looking to the planet's limb. (Credit: Space Telescope Science Institute and NASA)

Executive Summary

Mars exploration today is at a critical juncture. A series of successful orbital and landed spacecraft missions have revealed a planet with:

- A variety of environments that could be or could have been *habitable* to microbes,
- An early, more *Earth-like climate* that changed dramatically over time,
- A geologically recent *epoch of ice ages*, and
- A *dynamic planet* that still changes today.

These missions have also provided a first look at the *processes* by which the planet has evolved, addressing fundamental questions of planetary evolution and providing a valuable end-member in the comparative study of terrestrial planets both inside our solar system and beyond. The program of orbital reconnaissance and ever more capable landed missions has taken the program to the point that it can undertake the challenge of returning—for the first time—carefully chosen samples from the Martian surface for intensive study by the full capabilities of laboratories here on Earth. The *Perseverance* rover is on its way to Jezero Crater, where it will explore an ancient deltaic environment and collect samples for possible future return. NASA, in partnership with the European Space Agency (ESA), is developing follow-on missions for bringing those samples back to Earth during the coming decade, as endorsed by the *Visions and Voyages* Planetary Sciences Decadal Survey (National Research Council [NRC], 2011).

As important as Mars Sample Return (MSR) is—and it will result in a major step forward for planetary science—examination of material from a single site will not tell us everything that we need to know about Mars. Mars, like Earth, has a rich, complex history, with different locations capturing snapshots of its path in space and time. The history of one site must be integrated with a global context provided by both global observations and detailed local measurements at representative sites across the planet. Also, fundamental questions about Mars will remain related to its potential for life; the geological history of the planet; the history of its climate and the driving forces behind these changes; the evolution of geologic processes and the interior composition and structure; and more recent atmospheric, polar, surface, and interior processes. Answering these questions will require new flight missions in addition to those needed for MSR.

We have carried out a detailed analysis of the science and mission needs for exploring Mars, and we have surveyed the emerging capabilities in order to provide a new vision of what the Mars Exploration Program should be during this era. Our activity was driven by a recommendation from the mid-decadal evaluation carried out by the National Academies of Sciences, Engineering, and Medicine (NASEM) of NASA's progress on implementing the recommendations of *Visions and Voyages*. As part of its response, NASA chartered this Mars Architecture Strategy Working Group (MASWG) to assess the future of Mars exploration in addition to the current efforts to complete MSR.

In a rapidly changing environment of technical innovation, there are new opportunities to pursue the science, even while the challenges of retrieving samples from Mars are being met. However, as in the past, it will take a focused program that:

- Prioritizes the most important science, utilizing new missions across a range of mission size classes and science objectives that build on one another to meet the program objectives;
- Leverages the development of new technical capabilities (e.g., small spacecraft); and
- Works with different NASA directorates and international and commercial partners

in new—and possibly radically different—ways.

Mars exploration is an immense challenge, worthy of a program that has a history of meeting similar challenges.

We recommend a program that will investigate key areas of solar-system science, focused on examining Mars as the closest potentially habitable planet to the Earth. Mars presents:

- Outstanding access to environments fundamental to the search for past and/or present signs of life;
- An unparalleled opportunity to study climate and habitability as an evolving, system-level phenomenon, with Mars and Earth apparently having passed through similar stages as they evolved to their present states;
- The best place in the solar system to study the first billion years of the evolution of a habitable terrestrial planet;
- Outstanding opportunities to inform our understanding of the evolution of exoplanets by investigating its climate and prebiotic and possible biological history; and
- A compelling destination for human exploration and science exploration synergism.

While every solar-system body has its own story to tell, Mars is unique in that it retains today a resilient physical record of change over most of its history—predominantly in the rock and atmosphere for the early history and in the ice and the present-day environment for more recent times. Those records are accessible by measurement, at first from orbit and then *in situ* on the surface and in the atmosphere. Results from a continuing Mars Exploration Program will be both invaluable and necessary for interpreting data from MSR, for understanding the formation and evolution of our solar system, and for understanding the history of planets discovered outside of our solar system.

Fundamental scientific exploration can be carried out with missions ranging from Small Spacecraft class ($100–300M in full life-cycle cost) to Discovery- or New Frontiers-class (up to $1.25B). As proof of concept, we developed four series of missions (which we call "mission arcs"), each of which pursues a logical progression of missions in several different size classes by building scientifically and technically on each successive mission and its anticipated results. Within these mission arcs, the progress is often from initial investigation with smaller missions to detailed exploration of compelling science objectives with more capable missions. These arcs are examples of what the Mars Exploration Program could pursue, in consultation with the Mars science community.

The significant role to be played by small spacecraft derives from their high potential for carrying out significant Mars science, with the added excitement of being able to have a launch at nearly every opportunity every two years. More capable missions (Discovery, New Frontiers, Flagships after MSR) will be needed to address the most challenging objectives and discoveries. Implementation of the missions in several of these science mission arcs at the cadence proposed could be done for an estimated $300M/year through the first decade and $500M/year beyond that (all in FY20$); implementation of two of the arcs would cost about half this amount. Funding technology development and extended missions would require an additional estimated $150M/year. Pursuing four mission arcs appears to be affordable and would result in a broad, truly compelling and exciting Mars Exploration Program, while implementing fewer arcs would still allow progress in addressing fundamental questions about Mars. Clearly, the speed and depth of the science return will depend on the number of arcs and, therefore, on the funding invested in this program.

In addition, we are on the verge of initiating serious planning for human missions to Mars, with flights by NASA in the 2030s and perhaps earlier by commercial entities. A reinvigorated Mars program must be initiated now in order to support this planning and to be prepared for such missions. A robust Mars Exploration Program with new missions and payloads is necessary to provide sufficient knowledge about the Martian environment to allow us to carry out human missions safely and would provide a level of detail in our understanding of Mars to support planning the scientific exploration to be carried out by human missions.

The Mars Exploration Program that we are recommending can best be implemented as a separate program within the Planetary Science Division. The justification for having a separate, dedicated program falls into three areas—scientific, programmatic, and exploration:

- *Scientific:* Mars provides the opportunity to explore the full range of processes and properties on terrestrial planets under different boundary conditions from Earth. Mars' entire history is preserved in an accessible rock record that includes the first billion years. Mars also has key similarities with Earth that allow us to understand the processes that operated, with enough differences to truly test our models and our understanding.
- *Programmatic:* Mars is accessible enough that multiple missions can be flown to explore the different components of the Mars environment, including substantial access to the surface. Past experience has shown that the Martian environmental system is complex; understanding interactions between the different components, from the deep interior to the upper atmosphere, requires multiple missions that are well coordinated with each other.
- *Exploration:* Mars is NASA's stated long-term destination for human exploration. Precursor spacecraft missions are required in advance of human missions so that we can be ready for human missions to Mars.

Within this reinvigorated Mars Exploration Program, we make the following high-level recommendations:

- MSR should proceed as currently planned, as it will produce a major step forward in our understanding of Mars, as envisioned by *Visions and Voyages*.
- NASA should support missions that address fundamental science objectives at Mars in addition to MSR, using the full range of technically viable mission classes. During the MSR era, the emphasis should be on achieving other high-priority science objectives, while developing the technologies needed going forward.
- To the extent possible, missions and instruments should be openly competed; where specific investigations are desired, objectives can be defined and then opened to competition.
- For this next phase of Mars exploration, NASA should retain a programmatically distinct Mars Exploration Program. NASA should institute mission or budget lines that can allow Mars-specific missions, from small spacecraft through New Frontiers-class missions, to be strategically integrated into a program, with specific missions chosen and implemented *as appropriate for the science to be achieved.*
- A robust Mars exploration program will require affordable access to multiple places on the Martian surface and affordable long-lived orbiters. NASA should invest early to expedite the rapidly evolving small spacecraft technologies and procedures to achieve these capabilities at lower costs than past missions and work with international and commercial partners to achieve their delivery to Mars.

This Mars Exploration Program will address fundamental questions of planetary science and build on the new capabilities to do so, assuming a new steady funding line, at costs that are affordable while still maintaining a diverse portfolio across the solar system. NASA can provide the leadership and programmatic organization to work with the Mars community to choose and develop the right integrated sequences of missions that can address the compelling science; that can leverage the new technologies to make it happen; and that can conduct long-term planning to develop the needed partnerships both within the agency and with the ever-growing number of international space agencies, while developing new pathways for commercial partner involvement.

These are the challenges that can be met by the Mars Exploration Program to pursue compelling science at Mars during an era of MSR and beyond.

Burns Cliff, Endurance Crater, as imaged by the *Opportunity* rover. Some of the deposits on the walls show features indicative of having been deposited in standing bodies of water. (Credit: NASA/JPL)

Mars, the Nearest Habitable World – *A Comprehensive Program for Future Mars Exploration*

I. Introduction

The allure of exploring Mars goes back more than a hundred years to the time of the astronomers Giovanni Schiaparelli and Percival Lowell. They popularized both the scientific exploration of the Mars surface and atmosphere and the search for evidence of life. In that era, it was widely accepted that Mars could have intelligent life, even to the point that Nikola Tesla thought at one time in the early 1900s that he was detecting radio signals from beings on Mars. With the advent of the exploration of the solar system by spacecraft, Mars became the second planet to be visited by NASA spacecraft. Each spacecraft that has gone to Mars has carried a different set of experiments designed to measure different aspects of the planet, and each set of measurements has made fundamental discoveries about the red planet and contributed to our knowledge that in many ways is second only to the Earth in our detailed understanding.

However, Mars exploration today is at a critical juncture. A series of successful missions into orbit and to its surface have revealed a planet that once hosted a variety of habitable environments, an early more Earth-like climate that changed dramatically over time, a geologically recent epoch of ice ages, and a dynamic planet that still changes today. These missions have also provided a first look at the processes by which that all happened, addressing fundamental questions of planetary evolution and providing a valuable contrast in the comparative study of terrestrial planets.

Today, the high scientific and exploration value of Mars exploration have made it a major thrust of the robotic exploration of our solar system. As we have learned more and discovered the rich historical archive preserved at Mars, our fundamental questions about the history of the planet and how what happened there relates to other planets both in our solar system and beyond have deepened. These questions include (but are not limited to):

- Was there ever life on Mars, and could any still exist today at the surface or in the subsurface?
- What was the ancient climate that once hosted surface rivers and lakes like, what controlled it, and where did the CO_2 and H_2O from the early environment go?
- What geological processes have operated through time, and how have the interactions between the surface, interior, atmosphere, and external processes (including impacts and the Sun's behavior) shaped the evolution of the planet?
- What is the structure and composition of the interior?
- How do the present-day climate and polar caps behave, what controls their behavior, and how have they responded on various timescales to the changing tilt of the polar axis?
- Why are the Mars surface, atmosphere, and interior so different from those of Earth and Venus? And what does this portend for the study of exoplanets?

Finally, Mars is the only terrestrial planet beyond the Earth-Moon system that humans are likely to visit in the foreseeable future. That raises two additional questions:

- What knowledge is needed in advance for humans to be able to explore Mars?
- How can human explorers in orbit or on the Martian surface best address fundamental science questions?

These questions about Mars are fundamental to understanding the history of the planet and the implications of either a discovery of life or a demonstration that life was not present. That so many basic questions exist even after all of the spacecraft missions to the planet should not be surprising. As we know from our own planet, after the initial surveys, the questions become more detailed as to *how* and *why*, as well as *what*. Mars, like Earth, is a complex planet, and at an elementary level, we really do not yet understand how planets work or why Mars and the other terrestrial planets (including Earth) evolved as they did.

The program of orbital reconnaissance and of deployment of ever-more capable missions to its surface has brought the program to where it can undertake the challenges of returning—for the first time—carefully chosen samples from the surface back to Earth for intensive study by the full capabilities of laboratories here. *Perseverance* is on its way to its Jezero Crater landing site, where it will explore an ancient deltaic environment and collect and prepare samples for future return. In partnership with ESA, NASA is developing missions to bring those samples back to Earth, as endorsed by the previous Planetary Sciences Decadal Survey (NRC, 2011). That effort is itself a decade-long activity, involving development and flight of multiple spacecraft elements.

The scientific goals for Mars are to understand its evolution and its environment and to look for evidence of past life that might be retained in the rock record. The scientific results from past missions, from analysis of meteorites from Mars, and from Earth-based telescopic observations point unequivocally to sample return as being the next important step that will allow us to address many of the major scientific questions about Mars.

As important as MSR is—and it will result in a major step forward for planetary science—examination of a single site on a diverse planetary landscape with a complex history will not tell us all that we need to know. Also, not all scientific issues can be resolved by the analysis of returned samples. Questions about the nature of the present-day climate and its evolution and about global-scale processes and properties need to be addressed in order to have a broad picture of the context and implications of the sample analysis—understanding the global picture of Mars' behavior is necessary in order to put the sample-analysis results into the broader context of Mars as a planet. Additionally, as on Earth, a single location does not record all important evolutionary junctures of a planet's geologic history.

This next 10–15 years is a period in which MSR is being implemented. It also is a period when the human exploration programs will begin looking beyond current activities in order to establish human presence on Mars. It is a time when the very nature of exploration in deep space is rapidly changing, as new international partners and commercial entities bring new approaches, perspectives, and capabilities to the endeavor. What should the future of the Mars Exploration Program be during this era?

Our objective here is to examine the broad set of scientific questions about Mars and its relationship to the solar system and to exoplanetary systems, and to put forward the rationale for carrying out a Mars Exploration Program in addition to MSR. We examine the scientific questions that need to be addressed, the range of mission concepts that can address them, and how they might fit into a program of robotic exploration of Mars.

This MASWG arose out of the mid-decadal evaluation by the NASEM of the 2012 Decadal Strategy for Planetary Sciences (NRC, 2011). The charter for the mid-decadal evaluation (NASEM, 2018) included a request from NASA to evaluate the status and progress of the Mars Exploration Program. That evaluation included the following recommendation:

"Recommendation: NASA should develop a comprehensive Mars Exploration Program (MEP) architecture, strategic plan,

management structure, partnerships (including commercial partnerships), and budget that address the science goals for Mars exploration outlined in Vision and Voyages*. The architecture and strategic plan should maximize synergy among existing and future domestic and international missions, ensure a healthy and comprehensive technology pipeline at the architectural (versus individual mission) level, and ensure sustenance of foundational infrastructure (telecommunications, imaging for site certification, etc.). This approach of managing the MEP as a program, rather than just as a series of missions, enables science optimization at the architectural level. This activity should include assurance that appropriate NASA/MEP management structure and international partnerships are in place to enable Mars sample return." (p.6)*

In response, NASA chartered MASWG to make specific recommendations on the development of a science program and mission architecture that would address high-priority science objectives in addition to those that would be addressed by the MSR mission campaign; these are the initial steps in developing the full response to the questions from the mid-decadal review. The key components of the MASWG charter are:

"In response, NASA is forming a group of 12–15 scientists [plus engineers and managers] to develop such a Mars exploration strategic plan. The same Midterm Review endorsed MEP's current efforts to 'continue planning and begin implementation of its proposed... architecture to return samples from the Mars 2020 mission...' Given that priority, the tasks to be addressed by this panel are:

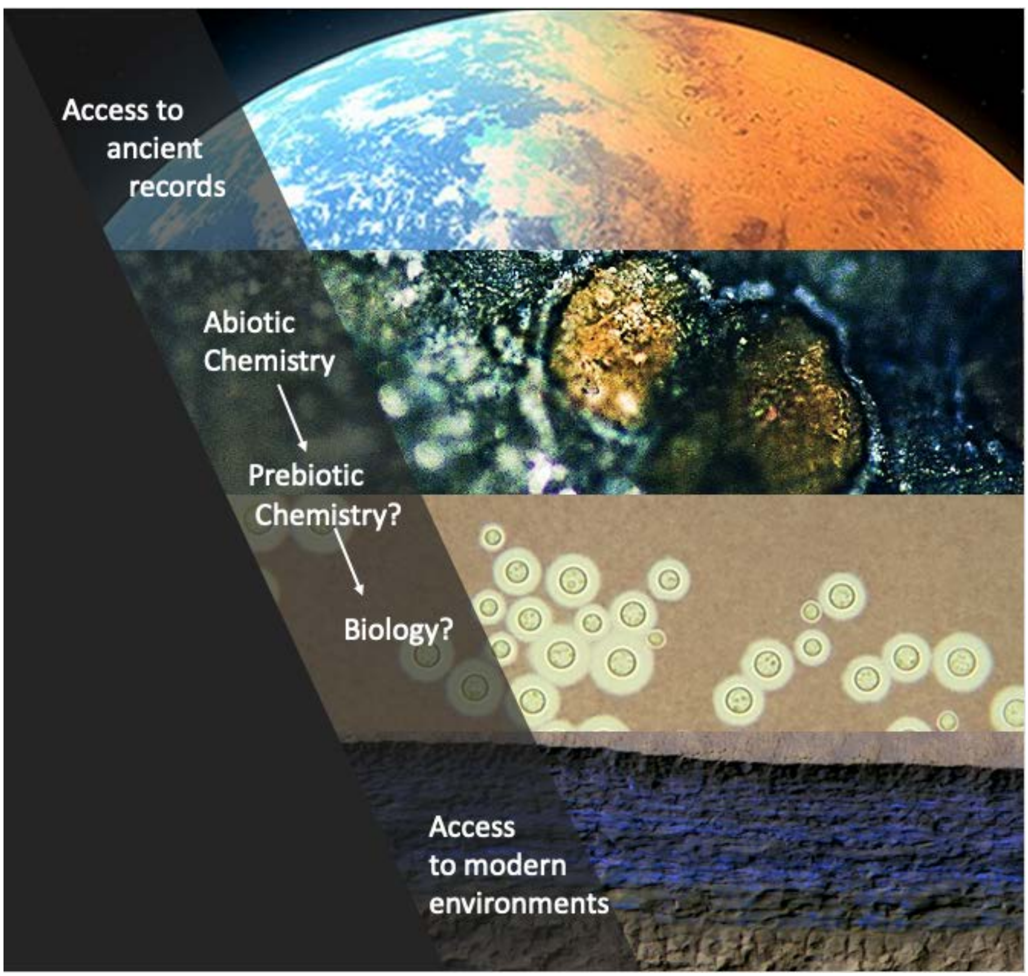
- *Determine what could and should be done beyond (i.e., in addition to or after) the Mars Sample Return campaign.*
- *Survey the compelling science addressable by various classes of missions during the period 2020–2035, building on the science goals outlined in* Vision & Voyages *and updated in the* MEPAG Goals Document*.*
- *Define a mission candidate portfolio to guide future MEP planning including, but not necessarily restricted to, missions in the competed small spacecraft, Discovery and New Frontiers categories [classes], which may also be considered by the upcoming Planetary Decadal Survey (2023–2032).*
- *Define strategic mission candidates, technologies, infrastructure, and partnerships (international and commercial) able to address compelling science in the specified time horizon, showing their programmatic linkage."*

The objective of MASWG is to build on the science priorities and mission concepts in the Mars Exploration Program Analysis Group (MEPAG) goals and objectives document (MEPAG, 2020) and in the decadal strategy (NRC, 2011). It was not intended to either update or replace those science priorities. In parallel with our committee work, the MEPAG goals and objectives were being updated, and MASWG benefited from briefings on the nature of those updates. Our report was completed in time to be provided as input into the new decadal strategy analysis now in progress.

In a rapidly changing environment of technical innovation, there are new opportunities to pursue that science, even while the challenges of retrieving samples from Mars are being met. However, as in the past, it will take a focused program that 1) prioritizes the most important science, utilizing a range of missions ("mission arcs") that build on one another to meet the program objectives; 2) leverages the development of new technical capabilities (e.g., small spacecraft); and 3) works with different NASA directorates and international and commercial partners in new—and possibly radically different—ways. It is an immense challenge, worthy of a program that has met challenges of a similar scope previously. MASWG believes that it can be done.

In what follows, the case that compelling science can and should be achieved at Mars in addition to MSR is developed, and key science questions are highlighted. While every solar system body likely has its story to tell, Mars is unique in that it provides a resilient physical record of that change over time—in the rock for the ancient climate and in the ice for more recent geologic times. Those records are accessible by measurements, at first from orbit and then *in situ* on the surface. Possibilities for obtaining the necessary data are discussed in the context of a program, enabled by new developments in spacecraft capabilities, including the maturing technology of small spacecraft. Some example proof-of-concept "arcs" of mission architecture are then presented to show how programmatic progress on high-priority science can be made during and after the present era of MSR.

Membership within MASWG was intended to be broad across science disciplines, degree of seniority/experience within their careers, and demographic diversity. While broad representation of the science disciplines was seen as necessary, there was no attempt to include "one from every discipline," as we strove to demonstrate proofs of concept for programmatic mission architectures and not to act as a science definition team for any specific queue of missions. Meetings and activities of MASWG are described in Appendix A.



This artist's concept illustrates the promise that the relatively pristine and accessible rock records of Mars—unique in the solar system—may tell the story of a planet's evolution from origin of life to its possible existence today.

II. Mars: A Compelling Target for Solar System Science and Exploration

II.A Overarching Themes

Mars has a uniquely accessible archive of the long-term evolution of a habitable planet. This record spans almost the entire range of ages of surfaces on the terrestrial planets in our solar system, with materials that may retain a record of the full range of processes that can occur. This provides a remarkable opportunity to study the interplay between processes and the means by which the primary characteristics of a planet have controlled them. The well-exposed and well-preserved 4-billion-year-plus record of physical and chemical planetary processes is unique in the solar system because of its high degree of preservation, accessibility, and importance to understanding planetary habitability. This record includes planetary formation, impact bombardment, interior and crustal processes, atmospheric and climate evolution, and potentially the origin and evolution of life on another planet. The high degree of preservation of materials at all ages allows these processes and their interaction to be tracked throughout time, and should provide a record that can be interrogated to understand the evolution of habitability by microbes and get a definitive answer as to whether life ever existed on Mars.

Habitability of a planetary environment depends on many factors. These include geologic supply of water and the building blocks of life, atmospheric control of climate and surface liquid water, and the Sun's influence on atmospheric evolution. We know that Mars, early in its history, had the necessary elements for life and had liquid water on its surface and in the near subsurface (Grotzinger et al., 2015). It also appears that today, much of the surface is hostile to life as we know it, and so the Mars Exploration Program has sought to exploit the preserved physical record to find evidence of life that may have arisen early on the planet. However, habitability is a time-dependent condition, dependent on climate and shaped by life itself, if it occurs. When we talk about Martian habitability, we mean the conditions that affect habitability, how they've changed through time, and the processes that have controlled them. Did the window for life's emergence close too quickly on Mars, or did it not close at all, with life even today in refugia not yet explored?

To deal with this complexity, we've divided the full range of science at Mars into five themes for discussion, recognizing that the crossover or interplay between areas is just as important as the discrete areas themselves. These five themes are as follows:

- Mars presents outstanding access to environments fundamental to the search for past and/or present signs of life.
- Mars offers an unparalleled opportunity to study climate and habitability as an evolving, system-level phenomenon.
- The best place in our solar system to study the first billion years of evolution of a terrestrial, habitable planet is Mars.
- Outstanding opportunities for elucidating the climate and prebiotic and possible biological history of Mars informs our understanding of the evolution of exoplanets.
- Mars is a compelling destination for human-exploration and science-exploration synergism.

These are summarized in Figure II-1, and each is discussed in turn below. The Martian environmental system is a complex, interconnected system, such that progress in one area ultimately requires progress in multiple areas. The processes occurring on modern Mars have operated in the past, while responding to different conditions (e.g., atmospheric composition and mass) and forcing functions (e.g.,

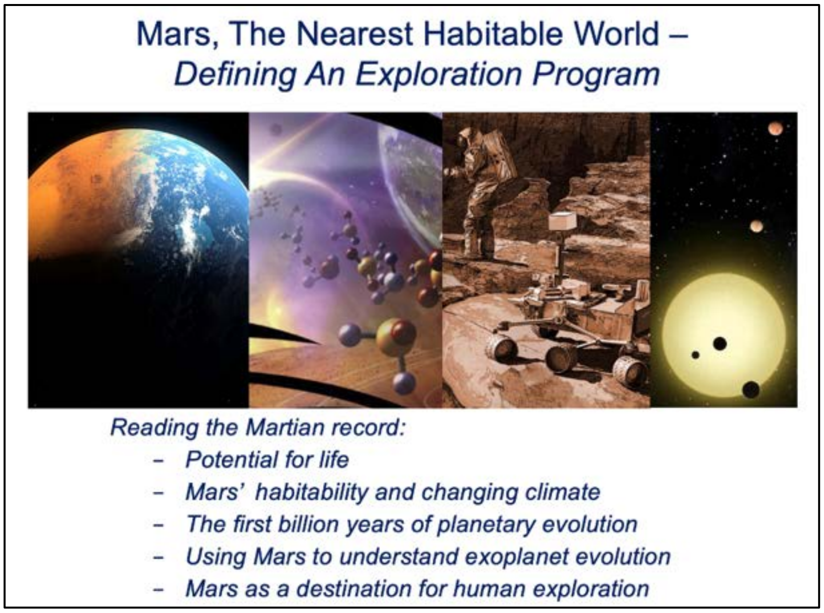


Figure II-1. Summary of the overarching themes for the scientific exploration of Mars as put forward in this report.

insolation at the poles or a faint young Sun). For example, the water cycle—the phase, distribution, and recycling of water—is important to life and alters the surface and climate. It is intimately connected to other cycles of CO_2 and of dust. Measurements addressing questions in one area benefit from measurements designed to answer questions in another area. More often than not, the answer to a fundamental question (such as whether life was present) requires integrating different types of measurements (biological, geological, meteorological) to arrive at an accurate understanding.

II.B Mars presents outstanding access to environments fundamental to the search for past and/or present signs of life.

The question, "Are we alone?" is by no means exclusive to science. Central to our sense of place in the universe, it is as much humanistic as scientific; however, it is in the rigorous methodology of planetary science and astronomy that an answer can be pursued, and we are now capable of doing so. Similarly, this fundamental question is by no means exclusive to Mars or even solar-system science, but multiple factors make Mars a premier venue in which to investigate it.

Mars preserves a record of early and diverse environmental conditions that is not present on Earth due to surface and crustal processes that have erased much of the first billion years of our planet's history. As a result, we largely lack direct observational constraints on the environments, conditions, and processes that prevailed during the critical time of life's emergence on Earth. The relatively intact record of environmental conditions during this period on Mars is thus a unique resource for understanding the emergence of life in the inner solar system.

Mars was habitable—was it ever inhabited?

From what we know today, Earth and Mars likely passed through similar phases of early habitability. If life is or was ever present on Mars, the early Mars rock record offers the potential to advance our understanding of life's origins in the specific context of the environments from which it emerged. Similarly, the absence of life on Mars would yield an equally valuable opportunity to explore a record of early chemical evolution that failed to give rise to biology and to understand that failure within the environmental context. Either alternative will serve to greatly improve our understanding of our own origin—how, and how commonly, life emerges in an Earth-like setting. More generally, as a rocky planet within its traditional stellar habitable zone, Mars serves as an important and accessible second example of the type of exoplanet that will be targeted in a telescopic search for life.

The search for evidence of life on Mars is both motivated and supported by spacecraft observations that have provided extensive environmental characterization and that inform our understanding of where and how to most productively conduct that search. Extensive observation of diverse surface environments, at scales from microscopic to global, has revealed the presence of conditions that could have supported life during Mars' early history and also preserved evidence of life over geologic time scales (Arvidson et al., 2008; Eigenbrode et al., 2018; Grotzinger et al., 2015; Hassler et al., 2014; Murchie et al., 2009; Stoker et al., 2010). Recent work has now identified a variety of possible "refugia"—caves, deep subsurface, subsurface ice, salt deposits, or some combination of conditions thereof—that could preserve modern records of life (alive within the most recent 10 Ma or now dormant) and that could potentially host extant life (Carrier et al., 2020). The ability to access these largely unexplored domains *in situ* is rapidly evolving (e.g., robots for extreme terrain, deep electromagnetic [EM] sounding from landers, and extended drilling) and the debate is about where is (are) the best place(s) to look (Hays et al., 2017; Onstott et al., 2019).

Can Mars ever tell us about the conditions sufficient for the origin of life?

The diversity of environments that are and were present on Mars, and their likely similarity to those on early Earth, is an important factor in the search for life. We lack a detailed understanding about the bearing of environmental conditions on life's emergence, and of the specific processes and settings that contribute to prebiotic chemical evolution and support the transition from abiotic to biological. Absent such knowledge, environmental diversity and broad similarity to a setting in which we know life can emerge become key considerations in targeting a search for evidence of life beyond Earth. Importantly, the extensive body of work that has sought to document evidence of life in ancient Earthly environments that are similar to those on Mars informs both the methodology with which to conduct such a search on Mars and the ability to interpret what we observe.

The *Visions and Voyages* Decadal Survey assigned high priority to the identification of ancient and modern habitable environments *and* the investigation of whether life emerged or now exists in those environments (NRC, 2011). The systematic characterization of Mars has revealed both ancient and potentially modern habitable environments, and we are now indeed poised to pursue a well-informed search for evidence of life there.

A sequence of missions has now commenced that represents the beginning, and not the end, of a quest to understand whether and how life took hold on Mars and persists into the present. NASA's Mars 2020 *Perseverance* rover mission is the next step in the search for evidence of ancient life, with the capability to detect macroscopic features associated with microbial communities, such as stromatolites, in exhumed sediments. Return to Earth of samples cached by *Perseverance* as part of an international MSR program will enable the most detailed and comprehensive analysis yet of organic composition and textural features in carefully chosen surface samples. Prior to that, ESA's 2022 *ExoMars* rover mission will search for organic molecular signatures of life in very early (Noachian) clay-rich sediments by drilling to a depth of 2 m at which the damaging effects of ionizing radiation should be minimized.

These missions have the potential to be profoundly enabling to a new chapter of *in situ*

Mars exploration whether or not they reveal evidence of life. Uncovering substantive evidence of life on Mars would motivate subsequent efforts to understand its emergence in the context of the host environment and its similarities and dissimilarities relative to life on Earth, and to determine whether it has persisted to the present in accessible refugia. The latter objective, to seek evidence of recent or extant life, will almost certainly require *in situ* investigation. Uncovering "hints" of life would surely motivate further sampling to seek definitive evidence, and finding no evidence of life would raise a series of sequel questions to be addressed *in situ*: Does the Martian record preserve evidence of abiotic or stalled prebiotic chemical evolution? Have environmental factors created a potential for false negative results? Could another of Mars' diverse environments, rather than the one sampled, contain evidence of life? Or is there something in the Mars environment that precluded an origin of life?

Ours could be the generation that discovers evidence of life beyond Earth. Advancement in planetary science and exploration technology have left us poised to do so as never before. The accessibility of known diverse habitable environments on Mars makes it a premier venue in which to seek such evidence, and existing technology or that which can plausibly be developed in the next decade allows us to do so.

II.C Mars offers an unparalleled opportunity to study climate and habitability as an evolving, system-level phenomenon.

The Martian climate has evolved dramatically through time, from an early phase with abundant liquid water to today's cold and dry surface. As discussed previously, Mars shows us that habitability is a *time-dependent* phenomenon governed by interacting processes that occur over a range of spatial and temporal scales. The longevity and accessibility of Mars' rock and volatile record allow us to study interactions among interior, atmospheric, and impact drivers of climate and habitability, and their evolution over time. The present climate is observable directly, whereas the record of past climate is stored in the volatile deposits of the polar caps, the crustal rock record, and evolutionary signatures present in today's atmosphere. This ancient record has been largely lost or altered on Earth, so the Martian surface provides a unique view into the early history of the solar system.

<u>The Ancient Climate: Whether cold or warm, how did early Mars get so wet? Solving this mystery is key to understanding planetary climates and their evolution.</u>

Mars' earliest period of evolution is particularly enigmatic. There is robust evidence for habitable surface conditions in Mars' early history, yet its orbit and the lower luminosity of the young Sun suggest that the surface should have been permanently frozen. This "faint young Sun" problem for Mars is one of the major outstanding questions in planetary science, with implications for Earth, Venus, and extrasolar planets. Significant progress has been made towards solving this problem over the last few decades, and it is now thought that the solution most likely lies in some combination of an enhanced greenhouse effect from a thicker early atmosphere along with local and/or transient factors. Nonetheless, major questions remain about the size and composition of the early Martian atmosphere, the surface conditions, and the early volatile inventory, including whether or not Mars ever possessed an extensive northern ocean (Wordsworth, 2016) and what the role was of the loss of Mars' atmosphere to space (Jakosky et al., 2018). For many planets in our solar system, including Earth, only scraps of evidence remain about conditions 3–4 billion years ago, but Mars' excellent surface preservation from this time period means that there is still a treasure trove of information from this habitable time period waiting to be fully accessed and studied.

Middle Mars: Understanding the factors controlling ice ages on recent Mars.

Mars' climate evolution since this early period is also unique in the solar system and has great potential to teach us about environmental processes that are analogous to, but still very different from, those on Earth. Because of its orbit and lack of the stabilizing influence of a large moon, Mars' axial tilt (its axial obliquity) evolves chaotically on timescales of millions of years and greater. Consequently, seasonal insolation patterns vary widely over geologic time, which has led to repeated migration of both CO_2 and water ice deposits across the planet's surface. As a result, volatile deposits both at the poles and at lower latitudes record a history of Mars' changing climate. Characterization of the extent and nature of these deposits across the surface is a major scientific goal (Diniega & Smith, 2020) that has significant implications for *in situ* resource utilization (ISRU) by future human missions, and possibly for astrobiological objectives. Understanding the evolution of volcanism, glacial processes, and subsurface hydrology from the Noachian (~4 billion years ago) to the present day is also of fundamental importance from a comparative planetology perspective.

Modern Mars: Current processes are key to the past.

Mars' present-day climate also continues to hold many mysteries and poses both challenges and opportunities for surface exploration. Present-day Martian meteorology is in some ways simpler than that of Earth, in part because of the lack of large standing bodies of water and the associated complexity in the hydrological cycle.

Nonetheless, the CO_2 volatile cycle, dust cycle, and water cycle all play significant climatic roles, and many aspects of their behavior on both short and longer timescales remain poorly understood (Haberle et al., 2017). Characterization of the dust cycle is an example of another area that is important both from a fundamental science perspective and for effective mission planning. Understanding all these processes on Mars adds to our knowledge of climate science as a general discipline by extension outside a purely Earth-like regime.

The distribution of habitable environments on Mars has changed over time along with the evolving climate. Exploration of Mars over the last several decades has established that the key ingredients for life as we know it (liquid water, a suite of life-essential elements, and a source of metabolic energy) were likely present at numerous, diverse locations across early Mars (see Figure II-2) (Hays et al., 2017; Onstott et al., 2019). These widespread environments may retain evidence of conditions in the early solar system at the time when life emerged on Earth and may even harbor vestiges of Martian life forms. Over time, the onset of cold, dry conditions has placed severe limitations on possible habitable environments on the planet's surface, but conditions suitable for life may have persisted to modern times in the subsurface (Stamenković et al., 2019).

A deeper understanding of the biological potential of Mars requires more detailed characterization of the habitable environments and how they changed over time, as well as determination of the underlying causes that brought about these changes. The findings can lead to new insights about the distribution of life, both within our solar system and beyond.

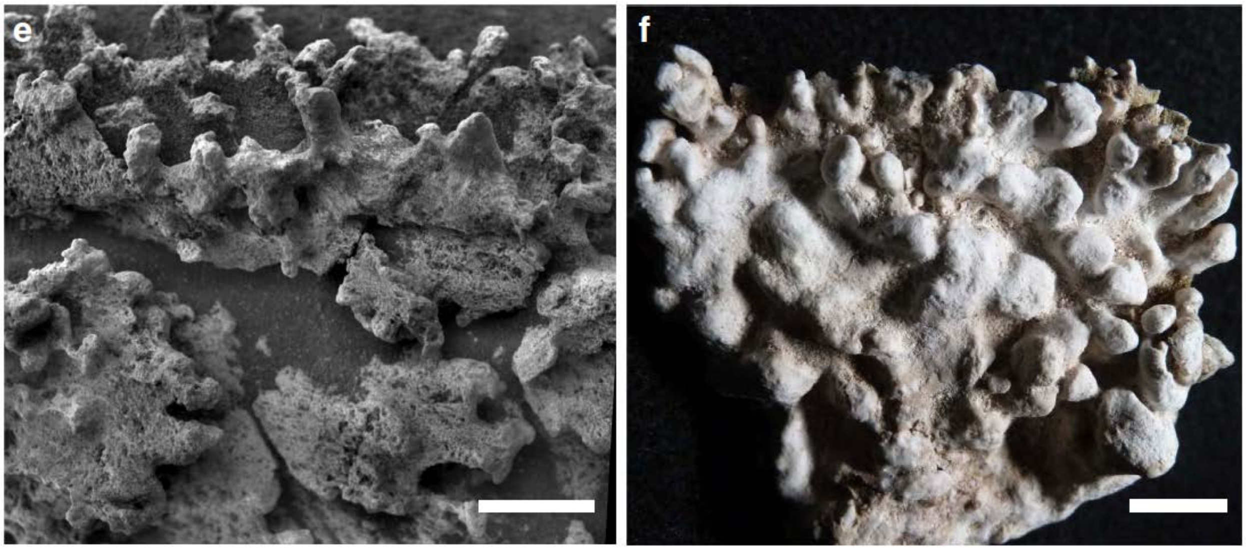


Figure II-2. Example of a habitable, and possibly once inhabited, environment on early Mars. The left image shows digitate silica deposits formed by a hot spring in Gusev crater, Mars, that was explored by the *Spirit* rover. The image on the right shows similar structures formed in a terrestrial hot spring in Chile. The terrestrial deposits contain abundant biosignatures indicating that biological organisms were present when they were formed and may have played a fundamental role in their formation. The similarities between the deposits raise the intriguing possibility that microorganisms may have been involved in the formation of the Martian deposits as observed for the terrestrial example. Image modified from Ruff and Farmer (2016).

II.D Mars is the best place in the solar system to study the first billion years of the evolution of a habitable terrestrial planet.

Many fundamental questions about the origin and early history of Earth persist due to the paucity of unaltered ancient materials. In contrast, Mars presents outstanding access to well-preserved ancient terrains that record the end of planetary formation, the early geophysical and geological history, the early evolution of an atmosphere, and chemical evolution possibly leading to an origin or existence of life. The crust of Mars is likely the only such relatively unaltered physical record in our entire solar system, as rocks of a similar age are not known to be accessible on Venus, and ancient terrains on the Moon and Mercury do not provide the same insight into atmospheric evolution, water, and habitability.

Mars contains the best-preserved rock record from the early period of planet evolution. Cratering chronology and superposition relationships show that >50% of the Martian surface is >3.5 Gyr old (Tanaka et al., 2014), encompassing pre-Noachian, Noachian, and Early Hesperian eras. Sediments in Gale Crater suggest an age of 4.21±0.35 Gyr for the surrounding watershed (Farley et al., 2014), crystalline igneous lithologies in Martian meteorites are dated as old as 4.1 Gyr (or older), and the oldest age in the regolith breccia NWA 7034 is 4.4 Gyr (Cartwright et al., 2014). These data show that Noachian-aged rocks encompass this critical early period of planetary evolution of a habitable planet, erased from Earth and not accessible on Venus.

Studying Mars will revolutionize our understanding of the coupled early geological, geophysical, and atmospheric evolution of Earth-like worlds.

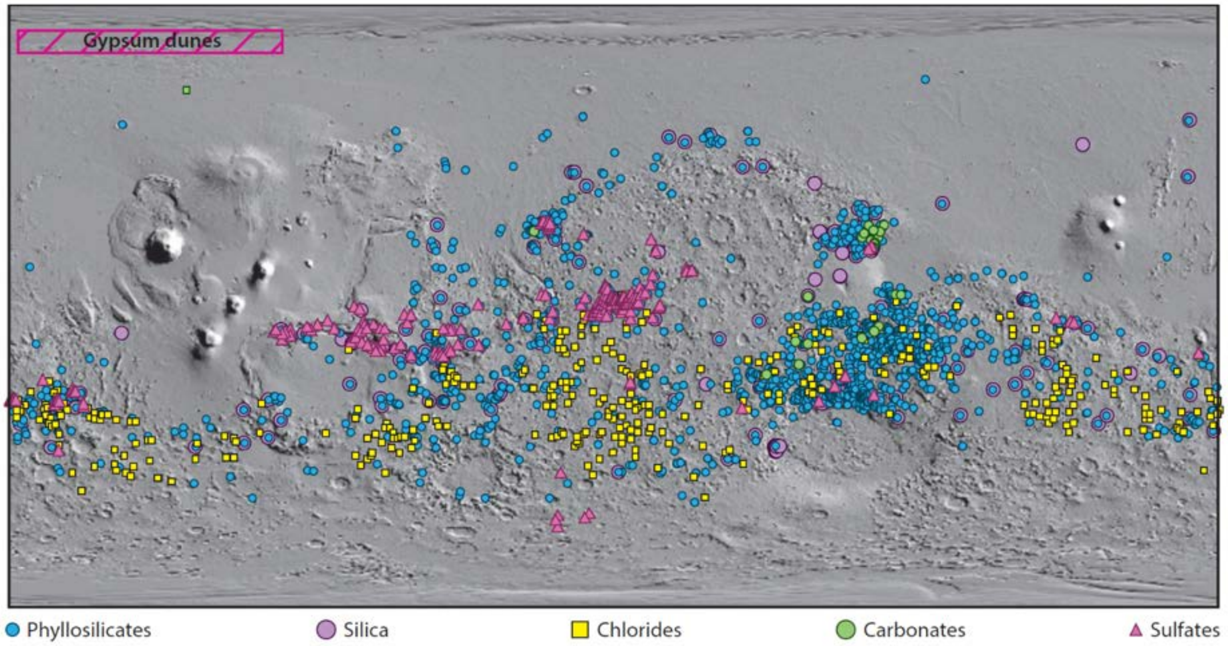
Geomorphology, geochemistry, and mineralogy from Noachian terrains show that the ancient well-preserved record is diverse.

Unaltered crystalline igneous rocks that record magmatic events in the mantle, crust, and surface are widely distributed in fault scarps, impacts (walls, ejecta, and central peaks) and volcanic flows (e.g., Mustard et al. [2005]). Impact and volcanically induced hydrothermal systems as well as groundwater aquifers are widespread. While well-known sedimentary deposits in locations like Mawrth Valles (Poulet et al., 2020) and Jezero Crater (Goudge et al., 2015) are testimony to active sedimentary systems from the Noachian era, there are numerous other systems in Noachian terrains. Multiple observations suggest that sedimentary processes were active in the early Noachian, including evidence for extensive erosion and deposition starting by the early Noachian (Irwin et al., 2013) and intriguing gigantic layered breccia blocks in Isidis Basin ejecta (Mustard et al., 2009).

This extensive sedimentary and aqueous mineral record also likely preserves key chemical records of the origin and evolution of the Martian atmosphere. The nature, duration, and composition of primary and secondary atmospheres on terrestrial planets are poorly constrained, and the record on Mars may provide important constraints on what Earth's and other planets' atmospheres looked like prior to the influence of processes like plate tectonics and photosynthesis (Lammer et al., 2018). In addition, Mars provides valuable insights into which properties of the atmosphere or planet enable an early warm climate and habitability. The faint young Sun paradox presents challenges for models of both early Earth and Mars (Wordsworth, 2016), but reconciling these models with geologic indicators for at least some periods of warm climates has led to novel hypotheses for warming mechanisms (e.g., Halevy and Head III [2014]; Ramirez et al. [2014]; Haberle et al. [2019]).

Mars provides a fundamental test for our models of accretion, differentiation, core formation, magnetic-field generation, and volatile evolution. However, the basic 3D architecture of the planet, including internal layering, thickness of the crust, nature of the core and composition of the mantle, and tectonic history, is still poorly understood (e.g., Plesa et al. [2018]), even with the new constraints from InSight (e.g., Banerdt et al. [2020]). These parameters define the key dimensions for the origin and fate of terrestrial planets, as the structure and dynamics of the interior are fundamental controls on the evolution of Mars, surface conditions, and the release of water and atmospheric gases. Mars also retains a record of early solar system bombardment that is distinct from that on the Moon (e.g., Moser et al. [2019]) that, if quantitative dates for major impact events and a better estimate of impactor flux at Mars can be obtained, would provide critical independent constraints on early solar system history.

A major outstanding question for the first billion years of Mars that illustrates the interconnectivity of key knowledge gaps is, "How and when did phyllosilicate-bearing Noachian crust become so extensively altered?" Scarps; impact central peaks, walls, and ejecta; and exhumed landscapes in Noachian crust are pervasively altered, but Hesperian rocks are much less likely to be altered (Bibring et al., 2006). Hypotheses include low-grade metamorphism, diagenesis, or hydrothermal alteration (Ehlmann et al., 2011); surface/near-surface weathering (Carter et al., 2015); alteration by impact-generated hydrothermal systems (Osinski et al., 2013); and alteration by an early supercritical steam atmosphere (Cannon et al., 2017). These observations are important for understanding models of water and climate history, so when and how this alteration occurred is fundamental for determining the first billion years of Mars' evolution.



Thousands of locations with water-formed minerals on Mars, identified with CRISM, OMEGA, and THEMIS, record the history of water-rock reaction over the first billion years and beyond (Ehlmann & Edwards, 2014).

The Martian geologic record will provide critical insight into which factors in planetary evolution lead to sustained habitable environments and possibly the origin of life.

Mars is currently the only planet where the surface is known to have made the transition from habitable (by microorganisms) to apparently uninhabitable, but the driving mechanisms for environmental change on Mars are still poorly understood. Evidence has accumulated for a wide variety of ancient habitable aqueous environments on Mars, including persistent lakes, extensive fluvial networks, widespread surface weathering, and hydrothermal systems (e.g., Grotzinger et al. [2015]; Ruff et al. [2020]; Arvidson et al. [2014]). We also now know that subsurface fluids were common on Mars (e.g., aquifers, diagenetic fluids, and fracture-hosted deep groundwaters) (Ehlmann et al., 2011) and that these subsurface environments may have provided a stable refuge for life (Michalski et al., 2013). However, we still do not understand how these surface and subsurface environments evolved over Mars history (their timing, persistence, and distribution), and we do not have robust constraints for the conditions under which they formed (climate, water properties, and diagenesis).

Because of these knowledge gaps about Mars and the lack of a detailed record from the early Earth, we do not yet have a model for which factors in planetary evolution control the habitability of terrestrial planets in the solar system and beyond. Studying early environments on Mars will enable us to move past the simple concept of the habitable zone to a more robust understanding of the habitability of Earth-like planets over time (Ehlmann et al., 2016). In addition, the depth and breadth of the Martian geologic record means that it is possible that Mars preserves evidence of prebiotic synthesis and the origin of life.

We haven't yet visited the oldest terrains on Mars in situ*, and many critical data sets have not yet been collected.*

The Mars 2020 *Perseverance* rover will visit ancient fluviolacustrine sediments in Jezero Crater that may date from the first billion years of Mars history (e.g., Goudge et al. [2015]) and may get the opportunity to visit ancient crustal exposures and impact basin deposits. *ExoMars* will also visit one example of ancient altered Noachian crust (Vago et al., 2017). However, these missions are just beginning to scratch the surface of the deep record preserved on Mars. In addition, several key global datasets are insufficient to address important questions. In particular, the geophysical properties of the Martian crust (gravity, magnetic field, etc.) are much less well-constrained than bodies like the Moon and can provide important insights into the early evolution of Mars.

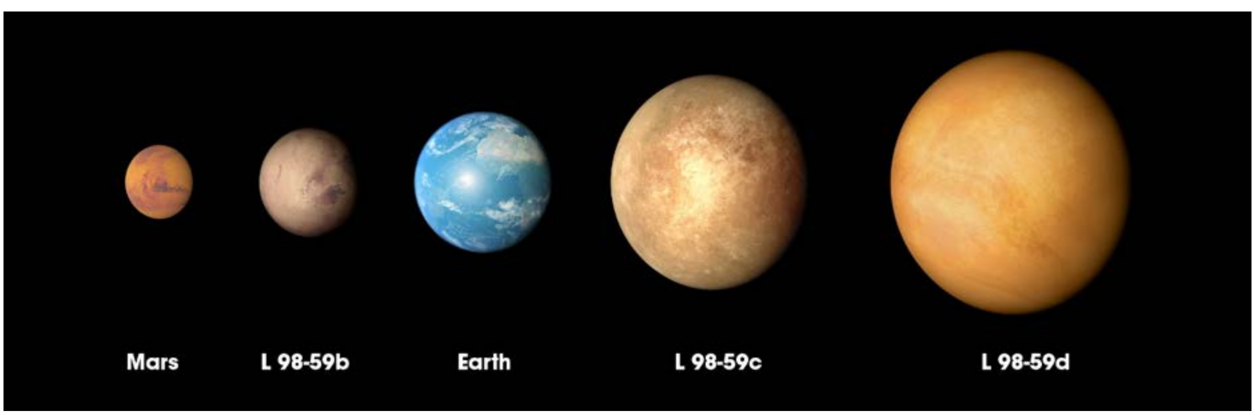
II.E Outstanding opportunities for elucidating the climate and prebiotic and possible biological history of Mars informs our understanding of the evolution of exoplanets.

The rapid growth in the study of exoplanets over the last two decades has affected many aspects of solar system planetary science, and Mars research is no exception. Over 4,000 exoplanets have now been discovered. For most exoplanets, the only information we have is the host star type and the planet's orbital distance, radius, and/or mass. However, observational techniques are improving continually, and for a number of planets, more detailed information has been obtained, including atmospheric composition and temperature structure. In some cases, the presence of atmospheric clouds and hazes has also been inferred (Madhusudhan et al., 2016).

The best characterized exoplanets so far are in the hot-Jupiter to sub-Neptune class. All of these are planets about 10 times more massive than Earth or more and possess hydrogen-rich atmospheres. Recently, atmospheric observations have begun to push down toward the rocky planet regime (e.g., Diamond-Lowe et al. [2018]; Kreidberg et al. [2019]), and the next decade will see a significant expansion of observations in this size class. Close-in, hotter rocky planets around red dwarf stars (M stars) will initially be the most observable cases (Morley et al., 2017), and surface properties (temperature, pressure, presence of liquid water) are likely to remain hard to retrieve, at least in the intermediate future (Loftus et al., 2019; Robinson et al., 2010).

Although exact Mars-analogue exoplanets remain out of reach for now, the broader intellectual links between Mars and exoplanet science are profound.

One particularly relevant link is atmospheric loss to space. Modeling suggests that the high rates of coronal mass ejection and XUV



Mars and Earth alongside artist's impressions of three exoplanets recently discovered in the same system by NASA's Transiting Exoplanet Survey Satellite (TESS) mission. Processes operating at Mars that affect its climate history also may be acting on exoplanets. (Credit: NASA) irradiation around M stars may be effective at stripping rocky-planet atmospheres in these systems, but many aspects of the fundamental dynamics, radiative transfer, and chemistry of atmospheric loss processes remain highly uncertain. Detailed observations of the Martian upper atmosphere provide a vital testbed for general models of loss processes that are also applied to exoplanets (Jakosky et al., 2018).

Because of the predicted efficiency of atmospheric loss for rocky exoplanets around M stars, it is also hypothesized that many such planets may have small surface water inventories compared to Earth (e.g., Tian and Ida [2015]). Here, again, Mars is an important solar system analogue, given that it has a small H_2O inventory, but (unlike, say, Venus) it still undergoes a water sublimation-condensation cycle with surface ice migration, has radiatively active water clouds, and exhibits coupling with the dust and CO_2 cycles. Many of the unique aspects of the modern Martian water cycle compared to Earth are likely to be of relevance to understanding arid exoplanets.

Mars also provides an important window into the links between atmospheric escape and planetary chemical evolution. The redox state of the Martian surface seems to have evolved significantly through time (Hurowitz et al., 2017; Lanza et al., 2016; Wadhwa, 2001), likely in large part due to the changing balance between hydrogen loss to space and supply of volatiles to the atmosphere through outgassing, impactor delivery, and other processes. This evolution has major implications for the possible development of life and for definitions of atmospheric biosignatures on exoplanets.

Also, highly relevant to exoplanets is "atmospheric collapse," the phenomenon whereby the atmosphere of an exoplanet condenses out on the surface due to extreme pole-equator or day-night temperature differences (Joshi et al., 1997). Having CO_2-ice poles in dynamic equilibrium with its CO_2-dominated atmosphere, Mars is a prime example of this phenomenon that is available for detailed study in our solar system. Specific process-driven questions regarding, for example, the efficiency of boundary layer heat transport at low pressures (Wordsworth, 2015) can be studied *in situ* at Mars to constrain models of planets orbiting many light-years away from our own Sun.

Mars: A solar system analogue for exoplanet evolution.

A final example is the long-standing debate on the relative roles of orbital distance from the host star and planetary mass in determining habitability. Mars has evolved from being a planet with habitable surface conditions in the distant past to a mainly inhospitable state today. This transition has been driven by a combination of factors, and there is debate about the extent to which Mars' distant orbit (which makes warm surface conditions hard to achieve) versus its small size (which likely caused early shutdown of plate tectonics, if it occurred at all, and enhanced loss of the atmosphere to space) was more important (Ehlmann et al., 2016). In the future, intercomparison of Mars with a range of exoplanets will allow us to bind solar system insights to new observations and build a general understanding of rocky planets on the edge of habitability.

Further example analogues beyond those given here are likely to emerge in the coming years as exoplanet science develops. Comprehensive study of fundamental processes on Mars can provide a strong foundation for understanding the complex pathways of evolution for planets where detailed observations will not be possible for a very long time. In all cases, Mars can serve as the natural laboratory or proxy for these numerous worlds, thereby enabling our understanding of the fundamental physical, chemical, geophysical, geological, and potentially biological processes that may occur there.

II.F Mars is a compelling destination for human-exploration and science-exploration synergism.

After the Moon, Mars is the next most accessible and, from a human perspective, the most hospitable destination in our solar system. Although Mars has long been a "horizon" goal for NASA and, to date, *human* Mars exploration has been limited to a series of architecture studies, current national policy explicitly calls for eventual human missions to Mars (Review of US Human Spaceflight Plans Committee et al., 2009; von Braun, 1969). In lieu of a formal Mars+ program, human *cislunar* exploration programs, such as the International Space Station (ISS) and Artemis, lay the groundwork for an eventual human mission to Mars. Many of the technologies, industrial infrastructure, flight systems, processes, and operations developed for cislunar exploration will be directly or indirectly extensible to Mars. We identify several areas in which there could be substantial synergy between the human and robotic Mars programs.

Potential for Significant Collaborative Value Between Human and Robotic Mars Programs

Human and robotic exploration of Mars are highly synergistic with each other. The robotic program can characterize aspects of the environment, knowledge of which is necessary for carrying out an eventual human mission; identify *in situ* resources that can support human missions; and develop the scientific background that will inform human missions and provide the intellectual underpinnings for the human scientific exploration of Mars. The human program, in turn, provides the immediacy for carrying out a robust and vigorous robotic program now; allows us to identify areas that require additional information and insights; and, when carried out, will do incredibly valuable science.

Scientific robotic exploration of Mars has benefitted—and will continue to benefit—a human Mars program by assisting in risk mitigation for crewed systems. For example, dust-storm data collected by the *Opportunity* rover has been instrumental in sizing human-scale surface power system concepts (Rucker et al., 2016), which in turn will allow tighter contingency margins, reducing mass and cost. The Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE) on the *Perseverance* rover will manufacture oxygen from carbon dioxide, demonstrating *in situ* utilization of Martian resources. Science can also contribute to and aid in identifying candidate human landing sites and hazard avoidance. Preparation for human exploration will utilize new scientific data for short-term mission needs (such as site characterization) and for longer-term exploration (such as resource availability mapping and dust-storm behavior).

New science investigations, such as understanding the dust cycle and the formation of low-latitude ice deposits, can support planning of human exploration activities, and the power and communications infrastructure needed to support humans at Mars can significantly improve data return for years to come. And as the most recent decadal survey (NRC, 2011) notes, "Although humans are not required for the return of samples from the Moon, asteroids, or Mars, if humans are going to visit these bodies, *collecting and returning high-quality samples are among the most scientifically important things they can do*."

Humans can more efficiently identify science of opportunity; conduct detailed *in situ* or laboratory analyses (e.g., geochronology, life detection); and operate complex machinery such as large drills. The enhanced mobility offered by human missions will expand science opportunities to previously inaccessible regions of Mars. Human missions will return invaluable sample suites for study on Earth, and human-exploration assets will enable increased data return bandwidth for long-term science use. Technology demonstrations on robotic spacecraft, such as those carried on the Mars

2020 *Perseverance* rover, are of enormous value to human mission planners, whose mission concepts can benefit from the subsequent maturation of these technologies.

Robotic-Human Program Collaboration Requires Prioritizing Filling in Science Gaps

One role of the robotic Mars exploration program over the next decade is to fill in our Martian science knowledge gaps and, as with cislunar exploration, pave the way for eventual human Mars missions. As noted in the most recent decadal survey (NRC, 2011), robotic and human exploration of space should be synergistic as both approaches drive the development of new technologies to accomplish objectives at new destinations.

The most recent MEPAG science goals document (MEPAG, 2020) contains substantial overlap between scientific and human exploration goals for Mars. These topics highlight fundamental knowledge gaps that span the range from atmospheric processes to crustal geophysics and satellite properties. However, ambiguity with respect to specific human-mission architecture has prevented prioritization of these knowledge gaps to optimize return for both science and human exploration. An eventual human Mars mission will likely have multiple objectives (e.g., sustainability, resource extraction, exploration, science) that will impact key factors like landing site selection, exploration strategies, and habitat design, so understanding the relative priority of each will help optimize robotic science decisions in ways that also support an eventual human mission. Important work is ongoing now via the Subsurface Water Ice Mapping (SWIM) activity (Morgan et al., in press; Putzig et al., 2020) to identify the probable locations of near-surface ice deposits that may help to provide water and fuel for human missions. Future missions will have to “prove out” the existence of the resources to be utilized. Even when objectives for human exploration and science overlap, they are not always identical in detail (e.g., *in situ* resource utilization wants to know how shallow the top of the ice is; science wants to know how deep the bottom is and why the ice is there). Good communication between the programs is needed, even when the objectives are overlapping.

The build-up of infrastructure to support exploration by humans based on the Martian surface will benefit science data return as well and robotic science missions can add to the communications and atmospheric monitoring activities. Just as on Earth, weather and climate observations and models will have applications to human activities on Mars and in its atmosphere.

Planetary Protection Challenges of Human Mars Missions

Human exploration of Mars is not without its significant challenges. One such challenge is the definition and implementation of appropriate Planetary Protection (PP) requirements. Although current low-Earth orbit/cislunar human exploration programs advance many operations needed for a human Mars program, PP requirements for Mars are likely to be significantly different from those implemented for the Moon; this is especially the case given the more stringent planetary protection-classification category for all of Mars than for any place on the Moon. Techniques used to sterilize robotic missions cannot be used on humans or their food, for instance.

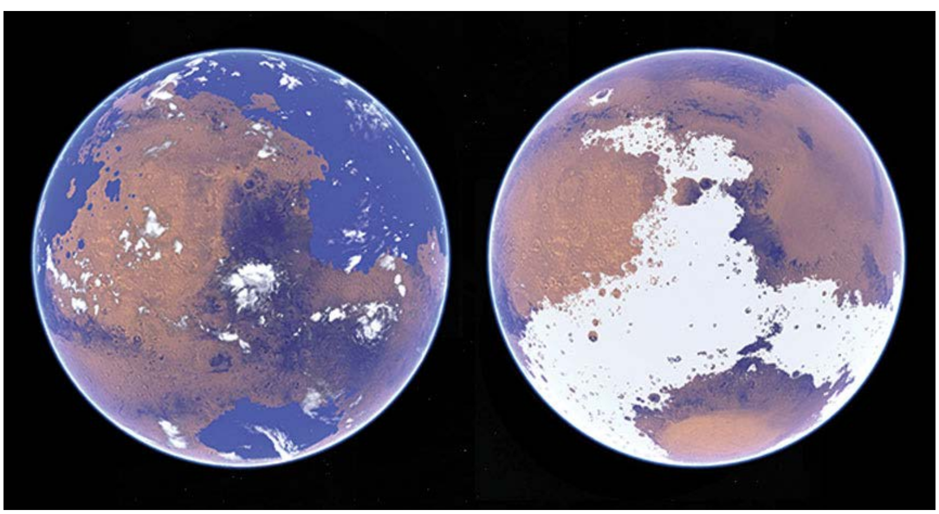
NASA recently reiterated its commitment to mitigating both forward and backward contamination related to human missions in NASA Interim Directive (NID) 8715.129. The NID established a path forward wherein knowledge gained from the ISS, Gateway, lunar surface operations, and robotic missions to Mars will be leveraged to prevent harmful forward and backward biological contamination.

II.G International and Commercial Players

Mars has become a destination for several international space agencies, including ESA (Mars Express [MEX], *ExoMars* Trace Gas Orbiter [TGO], and the *ExoMars* Rover and Surface Platform that has been delayed until 2022); the Japanese Aerospace Exploration Agency (**JAXA**: NOZOMI, Martian Moons eXploration/MMX); the Indian Space Research Organisation (**ISRO**: Mars Orbiter Mission/MOM); the United Arab Emirates Space Agency (**UAE SA**: Emirates Mars Mission [EMM]); and the China National Space Administration (**CNSA**: Tianwen-1), in addition to NASA and the Russian Roscosmos State Corporation for Space Activities. In July 2020 alone, three missions were launched to Mars: EMM (*Hope*), Tianwen-1, and Mars 2020 (*Perseverance*).

The opportunities for collaboration and optimization of activity with respect to Mars are clear. Sharing data for the scientific understanding of Mars and for planning future missions would be beneficial to all, as would ensuring that the proper infrastructure is in place to return the data acquired and to mitigate risk for all. However, this will require work.

Commercial entities, such as Space Exploration Technologies Corp., or SpaceX, have also announced intentions to take humans to Mars and to offer transportation of cargo to the Red Planet similar to their contractual role for the ISS. A model for this is NASA's Artemis Program, which envisions that both it and its commercial partners will play critical roles in the transportation of robotic craft and of astronauts to/from the lunar surface and the stations to be established there. As noted earlier (Section II.F), with the experience gained at the Moon, Mars would be the next destination for humans to explore *in situ*. Many of these plans for the Moon are not yet beyond the aspiration stage, but procedures are being developed, money is being spent, and hardware is being built for a 2022 launch. The lunar program has been organized and participants selected. Together, with independent commercial activities, there is much to be learned about this new way of doing business. One should not forget that Mars poses different challenges than the Moon, but also its own opportunities for enabling human exploration and perhaps established presence on another world.



Artist's impression of two visions for the early Martian climate: a warm and wet planet with oceans on the left, and a cold and icy planet with more limited liquid water on the right. Modern research suggests early Mars may have transitioned between these states, perhaps repeatedly, in its first billion years, although many questions about the nature of the early climate remain to be answered by future missions. (Credit: Harvard SEAS)

III. Findings

MASWG findings are conclusions about the Mars program based on the inputs we've received and the combined experience and participation in the Mars program by the MASWG members. The findings summarize our current understanding of the science of Mars, the accessibility of Mars for both human and robotic exploration, the role of MSR, the sizes of spacecraft missions necessary to carry out science and exploration, the specific potential utility of small spacecraft, the role of commercial enterprises or commercial-government partnerships, the value of international collaboration in the science and missions, and the relationship between the human and robotic exploration programs.

On this last point, MASWG had considerable difficulty in defining terms that relate to the distinction between human and robotic exploration. This terminology is inadequate because the science, mission objectives, and implementation do not divide easily. The division is not unique, whether we categorize by "human exploration" versus "robotic exploration," by "human missions" versus "science missions," or by missions carried out by the Human Exploration and Operations Mission Directorate (HEOMD) at NASA versus those within the Science Mission Directorate (SMD), and there are gray areas between every categorization. Here, we're going to use "human program" or "human exploration" to mean spacecraft missions that carry humans to Mars as a core activity or that directly support them, and "robotic program" or "robotic exploration" to mean missions that utilize non-crewed spacecraft that carry out scientific investigation of Mars. Awareness of the synergies and gray areas highlights the need to more clearly define the HEOMD and SMD roles in their complementary efforts. Doing so would further enable an SMD-based Mars program to coordinate efforts with the HEOMD that build on the strategies and strengths of a Mars program.

Finding 1: Scientific objectives at Mars.

Many of the most compelling scientific objectives needed to address planetary questions (including for exoplanets) can be most effectively achieved at Mars, and a coherent Mars program is required to make the best progress on those objectives.

Rationale: As described in Section II, exploration of Mars allows significant insights into planetary formation, impact bombardment, interior and crustal processes, atmospheric and climate evolution, and potentially the origin and evolution of life on a habitable planet. Having the entire 4 billion-year-plus history of Mars accessible in different locations allows determination of how these processes have operated and how they've interacted with each other through time. While other objects in our solar system contain a record of many of these processes, Mars is the only one that has access to the full range of processes throughout its entire history. Any understanding of how they've operated elsewhere in the solar system will, of necessity, have to come back to comparison with how they've operated on both Earth and Mars in order to enhance our understanding of planetary evolution.

Mars also provides the strongest insights available into the evolution of key aspects of exoplanets. Earth, Venus, and Mars span the range of planet size and show the effects in different combinations of solar insolation (i.e., distance from Sun), size, volatile inventory and interactions with an atmosphere, and presence or absence of a magnetic field. In particular, a major question about exoplanets is the evolution of their atmospheres and potential habitability. Mars' interactions with the Sun and the solar wind have driven significant loss of volatiles and change in climate, and the processes responsible for this at Mars are being explored in order to understand the ramifications for planets around other stars.

Understanding all of the different components of the Mars environment cannot be done with a single spacecraft mission—each mission sent to date, making different but complementary measurements, has revealed major new perspectives of Mars and has made fundamental discoveries about the planet. Even though we are asking more sophisticated questions that will require more detailed measurements, we do not expect that this period of discovery is over. Addressing the fundamental questions about Mars will require a series of missions that explore the upper atmosphere, lower atmosphere, surface, polar caps, and interior of the planet. These areas are not unconnected to each other, however. The missions addressing these components will need to be complementary to each other, both to ensure that they don't duplicate measurements and also to ensure that, together, they span the range of needed observations. Missions will need to be coordinated with each other in a way that ensures that the connections between different areas are exploited rather than falling through the cracks. This can be done most effectively within the construct of an overall program of Mars exploration rather than as a series of unconnected one-off missions. A more detailed rationale is given in Section IV.A.

Finding 2: Mars as a dynamic planet.

Two decades of exploring Mars from orbit and on the surface have revealed a currently dynamic planet with a diversity of ancient environments, many with the necessary conditions for habitability and containing clues to their evolutionary history.

Rationale: Mars today is a dynamic planet. As we explore in more detail, we are finding that the atmosphere has a complex seasonal and interannual interplay between the atmospheric circulation, the CO_2 cycle, the dust cycle, and the water cycle. The lower atmosphere that contains the major effects of these cycles connects to the upper atmosphere, where observations of the processes that are ongoing today inform our understanding of the long-term loss of atmospheric gas to space and the evolution of Mars' climate. The coupling between the atmosphere and the polar caps similarly informs our view of how the climate processes have operated on various timescales over the last 10 Ma, of how those processes extend to longer timescales, and of how the polar caps may retain a record of climate change on Mars.

The seasonal cycles combine to produce changes that are observable on the surface today. These include formation, changes in, and removal of dust streaks on the surface; the movement of sand dunes; and changes observable in the polar caps both in the CO_2 deposits and the exposed layers. All of the processes we observe today, operating at timescales from minutes to centuries, affect our understanding of the behavior of the entire system throughout Mars' history.

Evidence for additional processes that are likely to be operating today is seen in the gullies (which are small enough that it is unlikely that they could be ancient features that have survived to the present) and the recurring slope lineae (which are observed to form and evolve throughout a Mars year). Whether these relate to the transient or intermittent presence of liquid water at or very near to the surface, and their relationship to deliquescent minerals that can allow liquid water to be stable in small quantities at the present, for example, is not clear and requires further elucidation.

The incredible ancient and modern rock and volatile record preserved at Mars provides an unparalleled opportunity to understand the origin and history of the solar system and the potential for life beyond Earth. That extensive and diverse rock record is exposed and accessible on the surface today. The rock and atmospheric record can tell us about the history of climate change and the coupling between geological, atmospheric, and potentially biological processes. The global analyses from orbit and the local analyses carried out by landers and rovers tell us that Mars has all of the ingredients necessary to support life and that the chemical environment has been conducive to the presence of life—that Mars has been habitable by microbes throughout a large fraction of its life, and that it's a reasonable question to ask whether life actually has been present.

The Martian subsurface, with its clues to the formation of the planetary crust and interior and as a possible refuge of extant life, is largely unexplored. The basic division into a crust, mantle, and core is poorly determined at present; understanding the differences from Earth and Venus will be important for determining the factors that control formation and evolution of terrestrial planets. The complex geology observed by rovers at the surface tells us that the processes responsible for forming the surface have been as complex as on the Earth. While measurements tell us about surface ice and ice within the top few meters of the surface at intermediate and high latitudes, we do not know how deep the ice layer extends or whether there is a liquid water-rich layer beneath it in the crust. If such a layer is present, it could be the refugium in which life could exist even up through the present. Methane detection is still in dispute, yet trace gases measured at the surface may be our best window into subsurface habitability and the possibility of extant life.

The existing understanding of Mars' diverse environments and the capability to observe interconnected processes at multiple temporal and spatial scales leaves Mars uniquely suited for a systems-science approach. Mars is presently the only place beyond Earth that can be viewed through this lens. A program will be required to coordinate the observing strategies and campaigns required to realize the full potential that Mars offers in this regard. While we have characterized many aspects of the atmosphere and surface, detailed examination of the processes is very much needed if we are to understand how and why changes have occurred over time. That detailed study of processes—of transport, of photochemistry, of volatile transformation, of exchange at the atmosphere-surface-subsurface interfaces and at the exobase—is needed to have a complete understanding and to be sure that our models of processes are adequate such that extrapolation into past environments (e.g., a faint young Sun, a different atmospheric composition) will illuminate fundamental questions of planetary change.

Finding 3: Complete and accessible record.

For both science and exploration by humans, Mars has the compelling advantages of being the most easily accessible planet by both robotic and human missions and retaining a record of its geological, climate, and perhaps biological history throughout time.

Rationale: Among the compelling characteristics of Mars as a target for science and human exploration, the most striking are the longevity and apparent completeness of the geologic record exposed at the surface or in the near-surface. This record spans the evolution of this habitable planet from its origin through a period of sustained surface habitability to its current geologically active but uninhabitable surface and potentially habitable subsurface. The record locked into the geologic deposits on the surface is accessible by orbital and landed spacecraft. With continued technological development, remote access to the third dimension, the subsurface, is imminent. It is easily the best place in the solar system to study the first billion years of the evolution of a habitable terrestrial planet. This record has been severely degraded on Earth and has been erased or is not accessible on Venus, and the ancient terrains preserved on the Moon and Mercury provide little insight into atmospheric evolution, water, and habitability.

The beauty of Mars' accessible record is that it encompasses fundamental planetary transitions, from the time when the surface became geologically stable (pre-Noachian), to a planet that supports liquid water on the surface (Noachian), through an intense period of global volcanism and declining habitability (Hesperian), to a planet dominated by cold and dry surface conditions (Amazonian). While Mars was once undeniably habitable by microbes at the surface, that is no longer the case (except possibly in isolated or intermittent locations), and this record of multiple transitions is accessible to robotic and human explorers. Our understanding of the climate of Mars presents important issues. While the modern cold and dry Mars climate can be modeled with some certainty, making the planet's climate warm enough to support sustained liquid water at the surface 4 billion years ago when the Sun's output was 25% smaller is problematic. Yet the geologic evidence from orbiters, landers, and meteorites is unequivocal. The keys to unlocking this mystery are available in the accessible geologic record through the physical-chemical records of its early history (rock and sediments), of the recent geologic past (ice and dust), and of the long-term evolution of its atmosphere (gases and their isotopes), some of which are no longer accessible even on Earth.

The orbits of Mars and Earth make Mars readily accessible to robotic and human explorers from Earth on a regular basis when the planets align properly in their orbits. This occurs every ~26 months, with travel times between the two planets of 6–9 months. These characteristics make it possible to construct sequences of missions that build off the results and achievements of past and ongoing missions to achieve a compelling architecture of exploration.

Finding 4: Completion of Mars Sample Return.

The MSR program will produce a major step forward in planetary science and should be completed as planned.

Rationale: The *Visions and Voyages* Planetary Sciences Decadal Survey for 2013–2022 identified sample return from Mars as the highest priority Flagship mission for the advancement of planetary sciences. Implementation of this objective is currently underway, initiated by the launch of the *Perseverance* rover on July 30, 2020, and continuing with preparations for retrieval of *Perseverance's* cached samples for return to Earth. *Perseverance* will land in Jezero Crater on Mars in February 2021, a landing site that was carefully selected through a multi-year effort that included input from a large community of planetary scientists utilizing orbital remote sensing and landed experience.

Jezero Crater was selected as the landing site for *Perseverance* owing to its high potential for scientific return. A key feature of Jezero is that it hosts water-transported delta deposits which may retain evidence of ancient Martian life or its organic precursors. In addition, the landing site provides opportunities to examine a diversity of materials that will inform a substantially deeper understanding of Mars geologic and climate history. Analysis of these materials will provide new constraints on the potential for life in the solar system, the history of impact and magmatic processes, the timing and duration of liquid water on the Martian surface, environmental conditions during alteration and diagenesis of Martian rocks, and many other areas.

Return of samples from Mars to Earth will provide an unprecedented opportunity for detailed examination of materials from another planet and will doubtlessly lead to significantly improved understanding of both Mars and the solar system in general (Mustard et al., 2013). The ability to study the materials in terrestrial laboratories using state-of-the-art instrumentation with multiple complementary methodologies will allow for acquisition of information far beyond what would be possible with landed spacecraft. Among the many potential outcomes are a detailed characterization of the composition and distribution of organic compounds and other potential biosignatures, highly accurate age dating of geologic events, and fine-scale measurements of chemical elements, mineralogy, and isotopes that will lead to highly refined interpretations of geologic processes.

Whatever the results tell us about the geological and biological history of Mars, it will represent a leap forward in our understanding of our nearest neighbor planet. We reaffirm the value of completing MSR as an extremely high priority for Mars exploration and planetary sciences.

Finding 5: Utilize all mission size classes.

A Mars program can most effectively address the full range of key science objectives by appropriately utilizing missions in all size classes, in addition to MSR. The key is to match the mission class to the science objective.

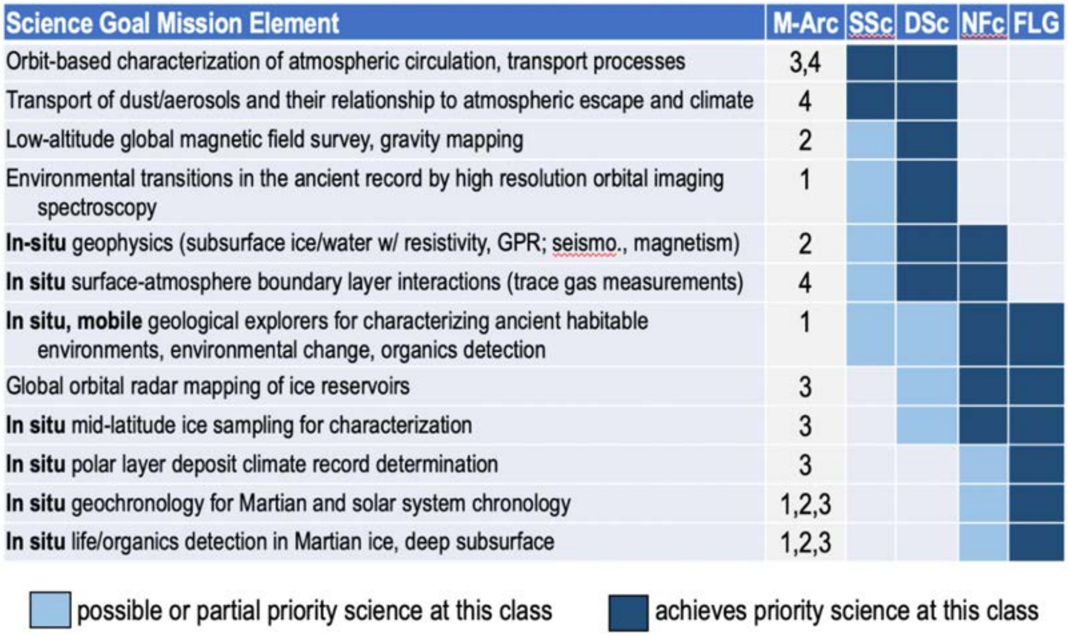
Successful NASA Mars missions have included Flagships (*Viking*, *Curiosity*), New Frontiers Class (Mars Exploration Rovers [MER], Mars Reconnaissance Orbiter [MRO]), Discovery/Mars Scout/smaller directed missions (Mars Pathfinder, Mars Odyssey Orbiter [ODY], Phoenix [PHX], Mars Atmosphere and Volatile EvolutioN [MAVEN], InSight), and small spacecraft (Mars Cube One [MarCO]). The range of capabilities flown was required to address the mission science objectives, which required orbital remote sensing and landed payloads, some with mobility. Fundamental science can be done with missions that span costs from Small Spacecraft class ($100M–300M in full life-cycle cost) to Discovery- or New Frontiers-class (up to $1.25B). A robust Mars Exploration Program also should utilize missions of all size classes, tailored to the challenge of the objectives. An exciting new development is the rapid advance in small-spacecraft technologies and in miniaturization of instruments, already in play for Earth orbit, raising the possibility that high-priority science can be achieved at more affordable cost (see the next finding and Section IV.B). Clearly, small spacecraft cannot address all of the major science questions (Section V), so the larger or more expensive missions have their role to play (e.g., MSR). The point is that a program can be most effective when the *mission class is matched to the science objective*, while remembering that a few small missions might answer the science need traditionally addressed by a large mission and might do so more cost-effectively. To realize this potential (Section IV.B), timely investment in the technological advancement will be needed (e.g., Finding 7).

Figure III-1 shows the mapping of mission class to some of the key measurements identified above (with *SSc*, *DSc*, *NFc*, and *FLG* denoting *Small Spacecraft*, *Discovery*, *New Frontiers*, and *Flagship* class, respectively). Where several classes are indicated as addressing the key measurement, this is often a case of following up on an initial discovery by utilizing greater capabilities (e.g., more coverage, better resolution, increased sensitivity, or a refined approach). Again, the key is to make the right choice of mission class for the objective, particularly in an integrated program where missions can build on one another (e.g., finding the right site for a landed investigation).

Finding 6: Small-spacecraft technology.

Rapidly evolving small-spacecraft technologies could enable measurements that address many key science objectives at Mars. This class of missions could become an important component of robotic exploration of Mars by enabling a higher cadence of scientific discovery at affordable cost.

Rationale: The last decade has seen growing capabilities of small spacecraft in Earth orbit and beyond for commercial, defense, and Principal Investigator (PI)-led scientific missions. The term “small spacecraft” encompasses a range of concepts but is commonly considered to be spacecraft having a mass of less than about 500 kg. Small spacecraft can include instrumentation within impactors (e.g., Mars landed mission ballast mass), CubeSats deployed by a main spacecraft at the destination, small satellites that launch as rideshare secondary payloads and independently proceed



Science Goal Mission Element	M-Arc	SSc	DSc	NFc	FLG
Orbit-based characterization of atmospheric circulation, transport processes	3,4				
Transport of dust/aerosols and their relationship to atmospheric escape and climate	4				
Low-altitude global magnetic field survey, gravity mapping	2				
Environmental transitions in the ancient record by high resolution orbital imaging spectroscopy	1				
In-situ geophysics (subsurface ice/water w/ resistivity, GPR; seismo., magnetism)	2				
In situ surface-atmosphere boundary layer interactions (trace gas measurements)	4				
In situ, mobile geological explorers for characterizing ancient habitable environments, environmental change, organics detection	1				
Global orbital radar mapping of ice reservoirs	3				
In situ mid-latitude ice sampling for characterization	3				
In situ polar layer deposit climate record determination	3				
In situ geochronology for Martian and solar system chronology	1,2,3				
In situ life/organics detection in Martian ice, deep subsurface	1,2,3				

possible or partial priority science at this class
achieves priority science at this class

Figure III-1. Traceability match from science goal mission element to Small Spacecraft (SSc), Discovery (DSc), New Frontiers (NFc), and Flagship (FLG) class missions. The numbers in the M-Arc column refer to the mission "arcs" (sequences of mission types) defined and described in Section VI.B.

to the destination, or independently launched spacecraft that take advantage of emerging small launch capabilities.

We will use the term Small-Spacecraft class (SSc) to mean spacecraft having a full life-cycle cost in the range of ~$100M–300M. SSc using present-day technology/capabilities could make high-priority scientific measurements from orbit (e.g., for study of atmosphere processes and climate). They could also provide a platform for other types of science measurements (e.g., network landers for geophysics, subsurface ice detection, or boundary layer processes) utilizing technologies that could be developed in the next 5–10 years. Small-spacecraft capabilities relative to cost, requirements, and performance need to be addressed programmatically to realize their full potential. Existing challenges to implementing Mars small spacecraft science missions include early identification of rideshare launch opportunities as well as enhanced technological capabilities in the specific areas of propulsion, communication, and entry descent and landing. More detail on the programmatic opportunity of small spacecraft during sample return is provided in Section IV.B.

Finding 7: Affordable access to the surface.

A critical scientific need for Mars exploration is affordable access to multiple places on the Martian surface with adequate payload/mobility to make the measurements that would revolutionize our understanding of the Mars system.

Rationale: The Mars program has reached a point where many of the most pressing measurements for key science topics can only be addressed *in situ* (see Figure III-1). These include (see Sections II.E and VI) ancient environmental diversity (cm-scale petrology and stratigraphy), modern climate variability (cm-scale analysis at the polar caps), biogeochemical cycles (isotopic measurements of volatiles in rocks), solar system chronology (*in situ* isotopes), and life detection (*in situ* organics) (e.g., Ehlmann et al. [2016]). Our growing knowledge from orbiters has pinpointed key locations that in several instances (e.g., ancient environments exploration, geochronology) require either precision landing or extended mobility.

In the post-*Viking* era, Mars landed mission costs have escalated at each launch opportunity. While the MER missions (*Spirit* and *Opportunity*) were executed at close to New Frontiers class (~$1.1B for two rovers in FY20$), roving or drilling are now perceived as and costed as being Flagship-level engineering challenges. Mars surface access cannot presently be accomplished in the Discovery-class cost cap without significant reuse of hardware (as with the PHX mission) or a fully non-NASA contributed payload (InSight), and competition rules now preclude more than 30% foreign payload contributions. Consequently, even traditional Mars landers may no longer be possible in Discovery. The loss of capability to conduct landed science within competed mission classes contrasts with the criticality of landed science for our understanding of the Mars system. Systems engineering investments in reducing the cost for access to the Mars surface would be a game changer for the quality and diversity of science possible at SSc-, Discovery-, and New Frontiers-class missions at Mars.

Lower cost, repeatable technology for surface landing and mobility at Mars to enable high-priority *in situ* science is crucial for the Mars program, allowing the program to address the diversity of the surface record of geology and climate, unravel processes driving the evolution of habitability, and search for life. There may be an opportunity to leverage technologies, work with commercial providers, or use contracting approaches derived from the Commercial Lunar Payload Services (CLPS) program in facilitating lower cost access to the Martian surface (see Section IV.C).

Finding 8: Commercial activities and potential partnerships.

Purely commercial or commercial-government partnerships for exploring or supporting the exploration of Mars, where the private entity bears a reasonable fraction of the investment risk, do not yet exist. A successful Mars-focused, CLPS-like program might serve as a programmatic vehicle to allow—at reduced cost but perhaps increased risk—development of technologies for future exploration as well as delivery of science payloads.

Rationale: As outlined in presentations to the Decadal Midterm Committee and to MASWG, NASA is open to innovative ideas and partnerships. However, purely commercial or public-private partnerships for deep space are relatively rare, and none for Mars has yet succeeded. NASA's 2014 Request for Information (RFI) for Mars Communications has not borne fruit. A particularly provocative example was given during the MASWG open fact-finding sessions, where we received a presentation from a SpaceX representative, who asserted that the SpaceX Starship might be able to transport cargo to Mars as early as 2022 and humans by 2024. Despite the exceptional success of the Falcon Heavy and Dragon launches, sending a Starship to Mars within two years appears to be an aspirational goal for a process that may take a few attempts to get it right. Even so, leveraging commercial approaches at Mars that are extensions of industry capabilities being developed for other purposes in space may be promising ways to engage partners in the technology developments needed for Mars orbiters and landers.

The programmatic core of the CLPS program is an IDIQ (Indefinite Delivery, Indefinite Quantity), competitively awarded, fixed-price contracting process. As described in Section II and in numerous studies that preceded this one, there is an abundance of science both beyond and complementary to MSR that should be conducted in order to fully understand Mars. The challenge is to keep the cost constrained while maximizing the potential for mission success. Given the expansion in the number of space entrepreneurs, the current success of CRS (Cargo Resupply Services, via the

Commercial Crew Program) and various low-Earth orbit (LEO) and geostationary orbit (GEO) ventures, examining the possibility for such an initiative appears to be very timely and reasonable, perhaps via an RFI or workshop process. An important element of this study would be to identify a business case that would provide the impetus for entrepreneurs to invest. Might specific hardware developed for the Moon be well-suited to Martian environments? An additional consideration is whether the cadence to Mars required to be commercially viable is sufficient and whether interleaving with similar requirements for lunar or asteroid exploration is sufficiently synergistic. More detail on these issues is provided in Section IV.C.

Finding 9: International collaboration.

There is tremendous value in developing collaborations between the many different governments and entities interested in Mars exploration.

Rationale: The exploration of Mars over the past two decades has involved many examples that highlight the benefit of collaboration and of coordination of activities between international partners. Such joint efforts encompass a range from the simple, but highly beneficial, planning of observations to facilitate opportunities for extended observational coverage and communication relay, to the contribution of instruments and personnel. Examples of the former include overflights and communication passes between NASA-landed assets and ESA's TGO, while recent examples of the latter involve NASA-funded U.S. investigators for TGO and European instrument contributions to the InSight mission. While these activities have traditionally been guided by the principle of "no exchange of funds," the scientific return from these international collaborations has been of tremendous value to all partners.

As noted in Section II.G, there are an increasing number of international players in Mars exploration. Participating entities now include the United States, ESA, Japan, India, Russia, China, and the United Arab Emirates. With this interest, the potential exists for collaboration and coordination as a way of increasing the amount of science that can be done and decreasing the cost to individual countries.

The continued exploration of Mars is expected to involve more complex and capable platforms but also constellations of smaller, simpler spacecraft. The anticipated greater costs of such endeavors added up over all missions, particularly within the framework of a dedicated Mars Exploration Program, will require a continued framework of international cooperation. A prime example of this need may be found with the MSR mission itself, in which both NASA and ESA are providing major components of the missions. However, efforts should also continue along the lines of the coordination and collaboration activities discussed above, particularly given the expanded opportunities envisioned by other findings and recommendations found in this report (cf. potential Mission Arcs in Section VI). A particular need to enable small spacecraft at Mars would be for the program to identify as early as possible rideshare (launch) opportunities among all public/private providers and to delineate requirements and timing, including the release of mass margin for secondary payloads by international and commercial entities, and to retain flexibility against changes in the primary mission that would affect rideshare opportunities.

Finding 10: Connections with the human Mars program.

The scientific and the human explorations of Mars are inextricably intertwined. Addressing science objectives will be an integral part of upcoming human exploration, and preparing for future human exploration provides one of the rationales behind having a vigorous robotic Mars scientific exploration program today.

Rationale: There is potential for significant value in collaboration between the human and robotic science Mars programs. The scientific and the human exploration of Mars are inextricably intertwined. Addressing science objectives will be an integral part of upcoming human exploration, and preparing for future human exploration provides one of the rationales behind having a vigorous Mars scientific exploration program today. Measurements that support planning for robotic exploration also can support the scientific exploration by humans on Mars, and vice versa. Such measurements include, but are not limited to, the need to understand current environmental conditions prior to sending humans, the search for accessible resources that can be utilized by humans, and the definition of scientific questions amenable to exploration by human missions. Discoveries are being made today that are significantly changing our understanding of the Martian environment and resource availability and thereby impacting our ability to carry out human missions. We expect such discoveries to continue in the foreseeable future, requiring interaction between the exploration directorates for science and for human activities

The potential for significant value requires a better prioritization of science knowledge gaps relevant to human Mars exploration. There has been insufficient interaction to date between the human and the robotic Mars exploration programs. This appears to be hampering efforts to define gaps in our understanding of the Mars environment that would be of high value to fill prior to committing to architecture or design for human missions. It's not clear which knowledge gaps must have better definition prior to human missions, which are "nice-to-haves," and which do not need to be addressed. Such a prioritization is necessary in order to define an orderly suite of missions or instruments that can address them.

Forward and backward PP challenges of human Mars missions are anticipated to drive additional science needs. With humans involved, it's not possible to keep contamination entirely out of the Martian environment. NASA's current PP requirements were not designed to deal with the difficulties of human missions. With the goal of PP being to support the science, requirements have to be realistic enough to not preclude human exploration at the surface yet not compromise the science significantly. We understand that NASA is in the process of defining PP requirements for the era of human exploration. Here, we note that these are significant issues that must be addressed in a timely manner. We have the expectation that PP for both human and robotic missions will evolve substantially over the coming decade. Detailed discussion of the PP issues is provided in Appendix B.

The *Perseverance* rover in the clean room at the Jet Propulsion Laboratory, Pasadena, CA. The rover is now on its way to Mars, where it will land on February 18, 2021. The rover carries a helicopter as a technical demonstration, a device (MOXIE) to demonstrate the feasibility of producing oxygen from the carbon dioxide atmosphere as a possible *in situ* resource capability for human explorers on Mars, and a suite of science instruments for *in situ* science and the preparation of samples drilled from the Martian surface for possible return to Earth.

(Credit: NASA/JPL)

IV. Programmatic Rationale and Future Opportunities

IV.A Why a Mars Program is Necessary

The question of why a Mars program is necessary to support the continued exploration of Mars splits into two parallel questions: what are the functions of a separately identified program that can provide support for Mars exploration beyond individual missions, and why is having a program necessary to support the exploration? We considered each of these.

Functions and characteristics of a Mars program.

The value of having a separate program to support Mars missions is its ability to carry out functions that lie outside of an individual mission and that affect more than one mission. Currently, a Mars Program Office exists at NASA's Jet Propulsion Laboratory (JPL) that oversees the various components of the program. The key functions of a program are listed in Table IV-1.

One example that shows the value of a program in supporting Mars exploration deals with the development of rover technology and operations. The first Mars rover was the *Sojourner* rover aboard the Mars Pathfinder, one of the first Discovery missions. *Sojourner* was roughly the size of a microwave oven and demonstrated the ability to traverse over the surface; the science value of using it was small. However, it led directly to the development and operations of the MER *Spirit* and *Opportunity*. These were larger, were well instrumented, and had operations involving substantial traverses and detailed exploration of multiple geological sites. Following that, the Mars Science Laboratory (MSL) *Curiosity* rover was larger still, with a more sophisticated payload and a longer planned life; traverses were planned and carried out, were more complex, visited more sites, and carried out more detailed scientific analysis at each site. Each rover was more sophisticated and more complex than those preceding it and had more involved operations allowing significant scientific results to be obtained. Without the ability to develop the rover, sampling, and operations capabilities on successive missions outside of the development of an individual mission, we would not

Table IV-1. Functions of a Mars Exploration Program.

• Allows coordination and continuity between missions to achieve science objectives beyond what a single mission or even a series of one-off missions could accomplish
• Provides feed-forward between missions on both science and technology, including use of small spacecraft as proof of concept for innovative approaches or measurements
• Allows development of infrastructure that can serve multiple missions (e.g., communications relay from orbit, landing-site characterization and certification using high-resolution imaging)
• Allows effective negotiation and coordination with international and commercial partners to take advantage of the tremendous interest in exploring Mars
• Allows focused development of required spacecraft and instrument technology in advance of mission selection (e.g., Mars Ascent Vehicle [MAV] development for MSR, PP concepts or implementations)
• Allows coordination between SMD and HEOMD to ensure strong connections between the human and robotic programs for Mars

have been able to implement these missions in a timely manner.

A second example involves the use of Electra communications relay radios on Mars orbiters to provide communications between landers and rovers on the surface and Earth. Without such communications relays, the capability to return data from the surface would be more than an order of magnitude smaller and the science return from surface missions would be significantly reduced. The Mars Exploration Program office at JPL provides coordination in the procurement and integration of the Electra equipment on the orbiters and in the planning of complex relay operations that currently span four orbiters and two surface platforms.

A third example, in the area of advance planning, involves the coordination between NASA and the space agencies of other countries or commercial entities. This, for example, is central to the coordination of hardware development and mission operations in collaboration with ESA on the MSR suite of missions.

There are other examples showing the value of having a program, including advance planning of new missions, development and oversight of PP protocols and implementation, public outreach that is coordinated across projects, development of hardware for future missions (such as the MAV or the Mars helicopter). These are all best carried out in a coordinated way rather than left to development by individual missions.

Why is a program necessary to carry out these functions?

A program is necessary when one is engaged in a series of missions that require: 1) development of technological capabilities that require long lead time for future missions, and/or 2) coordination between missions, either in operations or on science results that require integration across missions. A program can be developed for exploration of any object or series of objects. For Mars, the justification for having a program falls into three areas—scientific, programmatic, and exploration:

- ***Scientific**:* Mars provides the opportunity to explore the full range of processes and properties on terrestrial planets under different boundary conditions from Earth, including interactions between geological, geophysical, climate/atmosphere, space weather, and potential biological processes. The science spans a much wider range of topics (and requires a wider range of measurements) than can be accomplished by any single spacecraft or mission. Two aspects of Mars that uniquely allow exploration of the full range of scientific questions that, in fact, span the terrestrial planets are that:
  - Mars' entire history is preserved in an accessible rock record that includes the first billion years, and
  - Mars has key similarities with the Earth to allow us to understand the processes that operated, with enough differences to truly test our models and our understanding.
- ***Programmatic**:* Mars is accessible enough that multiple missions can be flown to explore the different components of the Mars environment and their interactions with each other, including substantial access to the surface. Having a Mars program allows us to carry out a mission that is focused on one aspect of the Mars system, knowing that other aspects will be addressed in complementary ways on other missions. Past experience has shown that the Martian environmental system is complex and that the different components interact with each other; understanding these interactions, from the deep interior to the upper atmosphere, requires multiple missions that are well coordinated with each other.
- ***Exploration**:* Mars is NASA's stated long-term destination for human exploration. Precursor spacecraft missions are required in advance of human missions so that we

can be ready for human missions to Mars, both with appropriate scientific background and with an adequate understanding of the Martian environment.

IV.B Small Spacecraft for Mars: A Programmatic Opportunity

The ongoing rapid development of small-spacecraft capabilities (e.g., as described at SmallSat/CubeSat Fleet Missions Database [https://s3vi.ndc.nasa.gov/cubesat/] or SmallSat/CubeSat Fleet Missions Graphic [https://s3vi.ndc.nasa.gov/cubesatfleet/] for CubeSat missions) has the potential to provide a new means of exploring Mars with more affordable and more frequent flights of payloads for scientific measurements and support of human exploration needs. Many science objectives will still need to be addressed by the more capable Discovery-, New Frontiers-, and Flagship-class missions (Section III, Finding 5). Even so, extensive use of small spacecraft at Mars is particularly appealing during an otherwise MSR-focused decade; such use could add a component to the Mars Exploration Program that achieves high-priority science with frequent launches at an affordable cost, while opening the way for commercial participation.

The Small Innovative Missions for Planetary Exploration (SIMPLEx) mission flight program and Planetary Science Deep Space SmallSat Studies (PSDS[3]) mission concept study program aim to demonstrate multiple compelling small spacecraft missions into the Mars system at development costs of less than ~$100M. As an example, the SIMPLEx Heliophysics mission EscaPADE (in Phase A/B at the times that MASWG was meeting) will make measurements to understand the interaction of the Mars magnetosphere with the solar wind and is being developed within a $55M cost cap (not including launch vehicle) (Lillis et al., 2020). Our synthesis of the 55 concept studies submitted by the Mars community (see Appendix A) identified several scientific priorities at Mars that can be addressed effectively by what we have defined as SSc missions, using an estimated cost range of $100M–300M (see Section III, Finding 5, Section VI.A and Appendix C). From orbit, these include characterization of atmospheric circulation and transport processes over multiple Mars years, low-altitude magnetic and gravity-field mapping, and high-resolution spectroscopy of the ancient record of environmental transitions. More ambitiously, SSc landers, either deployed from larger landers or as standalone small landers (once developed), could perform *in situ* geophysics and ice-depth measurements or characterize surface-atmosphere boundary-layer interactions that cannot be measured from orbit. With lower cost and shorter development times, SSc can be launched at a higher cadence than traditional larger missions and can respond more rapidly to new discoveries. To fully leverage these advantages, SSc must be planned and implemented through a distinct Mars program. Competed, PI-led science opportunities will allow the best concepts to be developed and prioritized at selection. The creativity of the community in developing ideas and mission concepts that can accomplish compelling science within the structure of small-spacecraft missions should not be underestimated.

Past SSc at Mars have had mixed success. In 2018, MarCO successfully demonstrated CubeSat capability in deep space with two independent Mars flybys that relayed communications during the InSight spacecraft entry, descent, and landing. In 1999, two Deep Space 2 microprobes attempted to land as penetrators released from the Mars Polar Lander prior to atmospheric entry; neither the two probes nor the carrier lander were heard from after the point of separation. While there are small Mars mission in development (e.g., EscaPADE), there is one now on its way to Mars: the recently launched EMM, in the higher end of the small spacecraft range defined here, carries a capable payload to observe the Mars lower and upper atmosphere once it enters a novel, quasiareostationary orbit. Its success would be an early demonstration for NASA and other space agencies of the viability of the small mission approach to achieving compelling science at Mars.

The ability to sustain a flight program of multiple SSc missions requires that an appropriate risk posture be used to ensure a reasonable probability of success for the portfolio as a whole. This will ensure that the program be resilient to single mission failures. Issues that would need to be addressed include:

- Possible elimination of dual-string systems
- Tailoring of risk posture with judicious relaxation of some oversight requirements; for example, by conducting small satellite missions as tailored Class D as per NPR 8705.4 and 7120.5E (as with SIMPLEx and some Earth Ventures missions)
- Further development of enabling technologies

The viability and cost tradeoffs of Class D or single-string missions for planetary missions (including cost trade-offs) would need to be determined separately for each mission's objectives; for example, longer-lived small spacecraft could be traded against a series of small spacecraft to capture climate variability over multiple Mars years, with each approach having different requirements. The CLPS program today is pioneering an approach of having private companies propose their own designs and having more mission-assurance autonomy (see Section IV.C). Both approaches have potential merit for Mars.

Key to reducing risk and costs for SSc is the early identification of rideshare opportunities, strategic investment in specific technologies, and examination of planetary protection issues and costs (see Appendix B). All Mars and Mars-flyby missions should be evaluated for rideshare opportunities (including secondary spacecraft and balance mass) because they would allow the lowest delta-v (and therefore lowest mass fraction in propellent) option for small missions. Taking advantage of launches from multiple nations planning direct-to-Mars or Mars-flyby missions in the next decade requires programmatic coordination to identify the potential specific opportunities or similar families of opportunities, delineate the requirements and the timing surrounding the confirmation of release of mass margin for secondary payloads, determine payload primary interfaces, and coordinate release of this information to SSc proposers/providers. With emerging new commercial small-launch capabilities at moderate cost, there may also be greater opportunities for sending spacecraft to Mars from LEO/GEO launches.

Key enabling SSc technology challenges are communications, propulsion, and entry-landing systems, the first two of which are undergoing rapid development now. Maintenance of a communications network at Mars also would be a key SSc enabler. Facilitating information sharing on propulsion capabilities and needs will facilitate SSc mission design. For small spacecraft landers, there are several promising, early-stage emerging concepts, but more work is needed to understand cost-capability tradeoffs between velocity at landing, precision targeting of a landing site, and mobility after landing.

The Mars program needs to develop SSc potential by matching spacecraft class and capabilities to the mission objectives within a reasonable risk/cost profile. This could be done programmatically by choosing missions in the appropriate size class while integrating them into coherent program lines that can achieve major science objectives. Several example Mission Arcs are provided in Section VI, each containing between 1 and 5 SSc missions over a 15-year period. Such a vigorous contribution to the Mars Exploration Program would be enabled by supportive programmatic actions. MASWG believes that the current SIMPLEx cost cap is too low to support a robust Martian small-spacecraft campaign, but costs in the range of \$100M–300M per mission would be more appropriate (see Section VI and Appendix C).

IV.C How to Involve Commercial and International Partners

<u>*Commercial Partnerships:*</u>

Recently, there have been multiple new entrants to the commercial space sector. Often characterized as "new space" or "entrepreneurial space," the most visible examples are the NASA-sponsored Cargo Resupply Services (CRS) and Commercial Crew Program (CCP) for transportation to the ISS, replacing the Shuttle. These initiatives began as an experiment in fixed-price contracting using NASA's funded Space Act Agreement (SAA) authority and were known as the Commercial Orbital Transportation Services (COTS) program. Successful bidders had to demonstrate substantial corporate investment. The final selected providers for CRS contracts ($2B each) were SpaceX and Orbital Sciences. To date, SpaceX has provided 16 successful flights and Orbital 10; each company has had one serious mishap in the program. CCP selectees are Boeing and SpaceX. These contracts are worth ~$4B for Boeing and $2.6B for SpaceX. As of this writing, SpaceX has successfully completed the first CCP flight to and return from the ISS with a two-person crew. Boeing is planning to launch its mission in the future. As a measure of the success of this overall approach, a Congressionally mandated study of the Falcon 9 development concluded that with a NASA investment of <$500M, the Agency has obtained a new reliable launch vehicle where the development cost would have been ~$4B under government business as usual.

In addition to the previous examples, there are multiple entrepreneurs focused on LEO business opportunities. The two initiatives that appear most likely to generate a positive return on investment (ROI) are 1) large constellations of relatively low resolution (1–3 m) remote-sensing satellites and 2) large constellations of LEO communications spacecraft intended to provide worldwide internet access. The companies and investors in these cases vary from small groups to major entities. However, emerging business enterprise sectors typically always have a high percentage of new starts and failures.

Currently, deep-space entrepreneurship is much less common. The best, and so far only, example of a current NASA-funded deep-space initiative with commercial partners is CLPS. The CLPS program is a task order-based IDIQ contract for payload delivery services to the Moon's surface, covering payload integration and operations, launch from Earth, and landing on the Moon. The CLPS contracts presently have a combined maximum contract value of $2.6B through November 2028. Selected companies are allowed to bid on specific task orders, which NASA has so far released at a cadence of one every few months. Currently, the only instance of a purely commercial deep-space project of which we are aware is the apparent long-term commitment of human travel to Mars by SpaceX and its founder Elon Musk. In February 2018, SpaceX—using its own funds—launched the first use of the Falcon Heavy, carrying Musk's personal Tesla roadster into a Mars-crossing heliocentric orbit. SpaceX has also embarked on an ambitious plan to develop the so-called Starship, a super-heavy launch vehicle capable of transporting passengers and cargo to Mars. (The Starship is designed to lift 150 tons to LEO.)

In order to continue fostering commercial partnerships, we suggest:

NASA and the Mars community should continue to monitor the possibilities and opportunities and consider the expansion of shared-risk investment in Mars-relevant technologies and capabilities.

Currently, purely commercial or commercial-government partnerships for exploring or supporting the exploration of Mars, where the

SpaceX Dragon capsule in its first trip to ISS, as an example of the type of commercial-government partnership that can support rapid development. (Credit: NASA)

private entity bears a reasonable fraction of the investment risk, do not exist. Leveraging commercial approaches at Mars that are extensions of industry capabilities being developed for other purposes in space may be promising ways to engage partners in the technology developments needed for Mars orbiters (both science-focused and communications-focused) and landers.

A successful Mars-focused CLPS-like program (perhaps Commercial Mars Payload Services [CoMPS]) could serve as a programmatic vehicle to allow development of technologies for future exploration as well as delivery of science payloads.

NASA and the Mars community should study the feasibility of adapting the CLPS program to Mars. The study should include a critical evaluation of whether there are commercial entities that can reasonably be expected to submit realistic fixed-price proposals for specific technological capabilities. The industry survey must take into account differences in traveling to and landing on the Moon versus the typical 7-month cruise to Mars; the ability to launch to Mars only every 26 months when the planets align; the much greater challenges of Entry, Descent and Landing (EDL); and the more stringent Category III, Category IV, or even Category V PP requirements for Mars versus the typical Category I or II classification at the Moon. Another important element of this study would be to identify specific hardware developed for the Moon that may be well-suited to Martian environments. An additional consideration is the cadence to Mars required for CoMPS to be commercially viable and whether interleaving with similar requirements for lunar or asteroid exploration is synergistic.

<u>*International Partnerships:*</u>

There exists a long history of international contributions to NASA missions, as well as U.S. scientists funded by NASA participating in missions led by other countries. The specific details of these efforts would vary, but a few principles have remained stable across the decades.

International efforts typically fall into one of three categories: coordination, collaboration, or interdependence. Coordination between missions, where data is shared but there is no hardware or software interface, have occurred many times. The ESA MEX mission and NASA assets such as MAVEN, Odyssey, and MRO have coordinated numerous times to facilitate scientific measurements and communications (in addition to actual provision of hardware between countries). One could imagine these missions, the EMM *Hope*, ESA's *ExoMars*, and future projects coordinating in a similar manner.

Collaboration, where there is typically a senior partner and a junior partner, is probably the most common form of joint effort. For perhaps 50 years or more, there have been instruments developed by other countries contributed to NASA missions. Radar Imager for Mars' Subsurface Exploration (RIMFAX) and Mars Environmental Dynamics Analyzer (MEDA), two instruments aboard the Mars 2020 *Perseverance* rover, were contributed by international partners. Most of the instruments on the NASA InSight mission were international contributions. Conversely, U.S. teams have been selected through competitive NASA solicitations to provide instruments on foreign spacecraft. An additional and common form of collaboration has been the NASA provision of the Deep Space Network (DSN) to enable communication links with the spacecraft. Typically, the barter arrangement of DSN time results in the selection of an instrument provided by a U.S. investigator. Such an exchange could well be part of future opportunities, including those described here.

While the failure of a single international contribution in coordination or collaboration almost never would result in the loss of the entire mission or failure to meet minimum success criteria, agreements that are interdependent carry a much greater burden. In NASA planetary programs, such interdependence has been relatively rare. For example, if the ESA-provided *Huygens* probe had been lost as it entered Titan's atmosphere, that loss would have compromised the overall Cassini mission results, but the *Cassini* orbiter would not have been in danger. On the other hand, the German-provided propulsion system for the Galileo mission to Jupiter was absolutely critical to mission success. Recently, NASA and ESA have publicly defined an approach for MSR that is highly interdependent. If the ESA-provided fetch rover or return spacecraft fail to operate, or if the U.S.-developed MAV does not work, the entire campaign is at risk.

We suggest that those key guidelines generally should be maintained for the following MASWG recommendations:

- *Acquire, maximize, and enhance the best science available worldwide.*

  International cooperation enables the distribution of cost and also provides an opportunity to find the very best scientists and instrumentation at a university or laboratory outside of the U.S. or NASA. As a consequence, virtually all of NASA's Announcements of Opportunity (AOs) and Research Announcements (NRAs) are open to the entire world, subject to the funding rules. We anticipate that this bedrock principle will continue in any solicitations that emerge from MASWG planning.

- *Establish well managed expectations of budgetary savings, complexity, and outcomes.*

  In the formulation period of any mission concept, there may periodically come a time when the projected cost including reasonable reserves exceeds the available budget. At this point, there are several options: descoping (i.e., eliminating requirements); adjusting schedule; or, in some cases, attracting an international partner who can provide some aspect of the mission. A clear-eyed recognition of what international collaboration can and cannot accomplish is necessary.

- *Continue "no exchange of funds."*

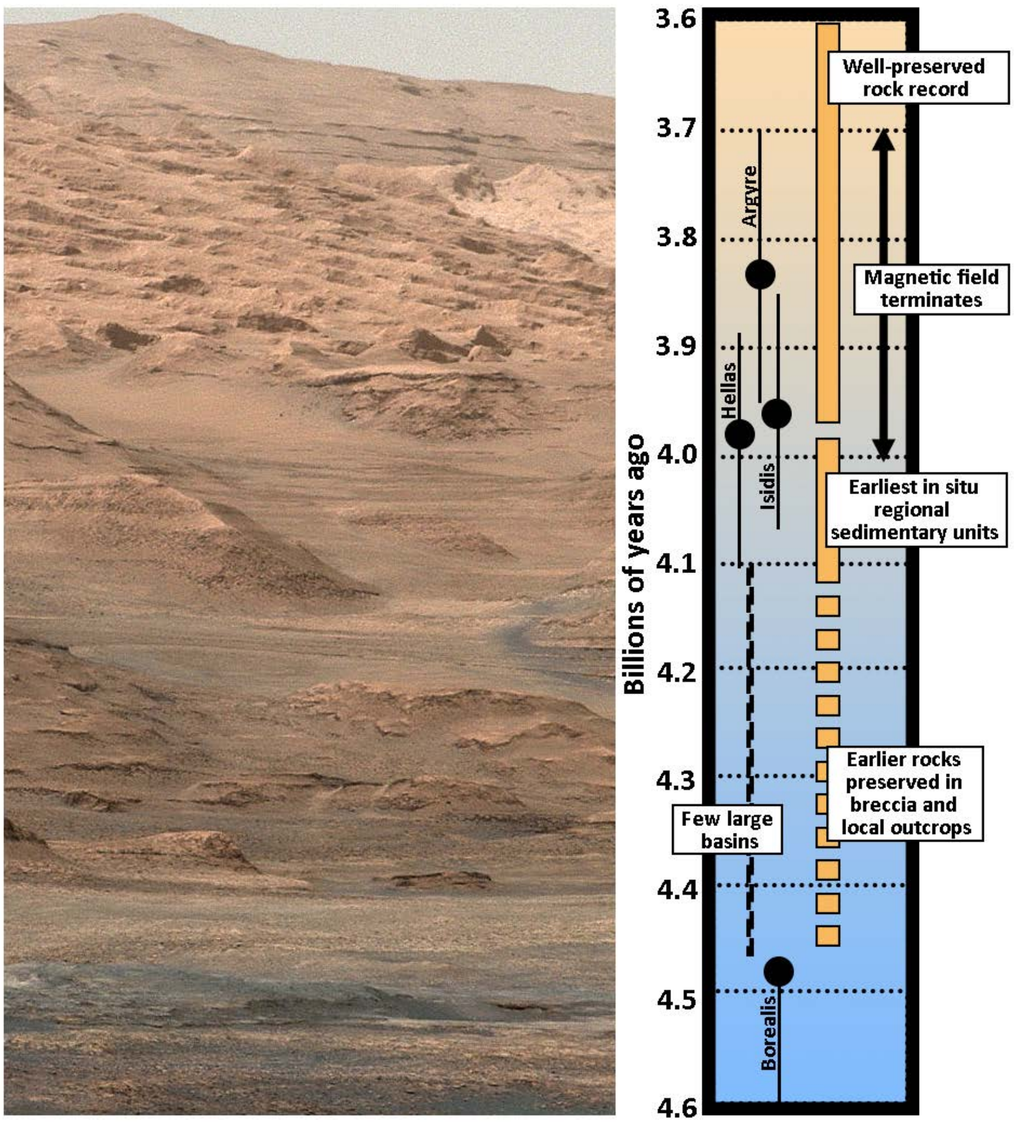
  Sovereign states must pay for their own instruments, science teams, and other contributions. This principle must include support for any interface management. Such an approach is usually considered to be a "barter" arrangement.

- *Define a clean interface between contributions.*

  This guideline is required to maintain cost control, stabilize requirements, and meet schedule. The ESA-contributed *Huygens* probe and most foreign instruments that "bolt on" are good examples of a clean interface.

- *Create clarity in the management structure*.

  This principle includes procedures for dispute resolution, processing data, announcing scientific results, conducting the development engineering, and mission operations. A prime example of this principle has been the International Space Station.



Left: An example of a deep sedimentary record exposed on Mars on the slopes of Mt. Sharp in Gale Crater, as imaged by the *Curiosity* rover. Right: Selected events from the geologic history of the first billion years of Mars, including magnetic field cessation, impact ages, and ages for regional sedimentary rock units.

V. Recommendations

MASWG recommendations are broken into two distinct components. The first contains five high-level recommendations about the overall nature and structure of a reinvigorated Mars Exploration Program. The second contains 10 additional specific recommendations that will ensure that the resultant Mars Exploration Program can be successful. In each case, recommendations are given and followed by elaboration and rationale, as appropriate. The structure of a program that will be responsive to these recommendations is discussed in Section VI.

V.A High-level Recommendations

Recommendation 1.

Mars Sample Return should proceed as currently planned, as it will produce a major step forward in our understanding of Mars, as envisioned by *Visions and Voyages*.

Rationale: MSR was the highest priority put forward for a flagship mission in the 2011 NASEM planetary sciences decadal strategy, with the understanding that there would be a commitment from NASA to complete the return in the next decade of 2023–2032. We strongly reaffirm that the suite of missions to bring samples back should be carried out. The material in this report is not intended in any way to represent an alternative scientific or programmatic pathway to carry out sample return. It is intended as a proposed program to be carried out in parallel with sample return to ensure that we can obtain a broad and integrated understanding of Mars as a planet.

Recommendation 2.

NASA should support missions that address fundamental science objectives at Mars in addition to MSR, using the full range of technically viable mission classes. During the MSR era, the emphasis should be on achieving other high-priority science objectives, while developing the needed technologies for going forward.

Rationale: Despite the very high science value of MSR, it does not address all high-priority science objectives necessary to give us a broad understanding of the evolution of a habitable planet. In order to do this, and to obtain the necessary knowledge on the Martian environment and the science background required to support human missions in the next two decades, NASA needs to implement additional science missions. High-priority science objectives can be met using the full range of technically viable mission classes, from small satellites up through New Frontiers-class missions and, post-MSR, including possible Flagship-class missions. The budget necessary to carry out such missions will be discussed in Section VI. Within funding levels that realistically could be made available, both high-priority science objectives and technology development necessary for follow-on missions in the next decade could be supported.

Recommendation 3.

For this next phase of Mars exploration, NASA should retain a programmatically distinct Mars Exploration Program. NASA should institute mission or budget lines that can allow Mars-specific missions, from small spacecraft through New Frontiers-class missions, to be strategically integrated into a program, with missions chosen and implemented as appropriate for the science to be achieved.

Rationale: The technology development required for future missions, the advance planning of missions and their implementation, the integration of missions into a program that addresses science objectives appropriately, and the coordination of missions that allows for support between missions can be carried out in a robust way only if there is a well-defined Mars program that can pursue a long-term vision with independent authority and budget line. When Mars missions compete against the rest of the solar system in the Discovery and New Frontiers Programs, they can and have been competitive, but it is unlikely that they will be selected in a manner that is timely for supporting other missions or that the selected science will be integrated with that from other missions in an optimally coherent and coordinated way. Independence here means having the mission or budget lines, authority, and accountability where planning and implementing a program can be done within those constraints. To succeed, it is imperative that sufficient flexibility be built into the program so that the science to be achieved first be identified and then the mission class appropriate for that science selected, rather than defining the mission class first and then fitting the science within its capabilities (this applies whether the action is either to expand scope or reduce scope).

While MASWG was formulating its preliminary results, NASA made two announcements that affect the structure of the Mars program and bear on this recommendation. First, the next two MSR flight missions were separated from the rest of the Mars program, with a program director appointed who reports directly to the SMD Associate Administrator. While the roles and responsibilities of the MSR campaign and the current Mars Exploration Program are still being worked out, it is expected that this new MSR Program will be highly focused, keeping the flight developments on track technically and financially. Second, the current Mars Exploration Program Director has left that position for a new position in the office of the Associate Administrator for Strategy and Plans as NASA's Senior Advisor for Agency Architectures and Mission Alignment, where he "will lead an update of the Agency's Mars exploration planning, including further development of our investment strategy and partnership opportunities… Overall, he will provide the principal focus for the coordination and integration of cross mission alignment and planning efforts with senior staff from the mission directorates, centers, other support organizations, and external partners" (T. Zurbuchen [SMD Associate Administrator], personal communication, September 1, 2020).

The existence of three separate organizations that each appear to have some oversight responsibility for different aspects of the Mars program, and the existence of multiple points of contact and interaction between the missions that appear to reside within each program, leave open the potential for conflicts in the goals and in the explicit requirements and directions for each program. This is not the first time that these issues have arisen: In the wake of the failures of Mars Climate Orbiter and Mars Polar Lander in 1999, the final report from NASA's Mars Program Independent Assessment Team (MPIAT, chaired by A. Thomas Young) stated, *"The NASA Headquarters‑JPL interface was found to be ineffective as the result of a failure to clearly communicate. Multiple interfaces at NASA Headquarters for the JPL Mars Program Manager caused difficulty at both organizations. The ineffective nature of the interface is judged to have had a negative impact on mission success."* MASWG did not have the opportunity to hear directly about these changes, to discuss their ramifications, or to propose potential alternative management structures, but we do want to identify these apparent conflicts between management lines as a potentially significant issue for the Mars program going forward.

Recommendation 4.

To the extent possible, missions and instruments should be openly competed; where specific investigations are desired, objectives can be defined and then opened to competition.

Rationale: The value of competing both instruments and missions has been demonstrated numerous times, in terms of both the robustness and cost of development, and the quality and value of the science that is returned. There are multiple approaches to competing missions. Mission concepts and the science to be addressed can be competed fully, as was done with the Mars Scout Program and is being done in the Discovery Program today. Science objectives can be defined up front, with competition for implementation, teams, and instruments, as is done today with the New Frontiers Program. Or competition can be carried out for integrated science payloads to sit on a spacecraft provided by NASA direction and managed by a NASA center, as was done with the Mars Exploration Rovers. Where mission science or programmatic objectives are defined up front, open competition to provide instruments or science investigations should be carried out.

Recommendation 5.

A robust Mars Exploration Program will require affordable access to multiple places on the Martian surface and affordable long-lived orbiters. NASA should invest early to expedite the rapidly evolving small spacecraft technologies and procedures to achieve these capabilities at lower costs than past missions.

Rationale: The Mars program cannot be robust in investigating the highest scientific priorities unless lower-cost approaches can be developed for long-lived orbiters; small spacecraft; and EDL for landers and rovers. Capabilities in these areas are evolving rapidly at present, especially for small spacecraft, but an investment from NASA will be required to ensure that these capabilities can be utilized in a timely manner for Mars missions.

V.B MASWG Recommendations for a Successful Future Mars Exploration Program

In addition to the high-level recommendations made in the previous subsection, we present 10 specific and detailed recommendations that we believe will help to ensure the success of the revamped Mars program. These generally follow from and elaborate on the high-level recommendations discussed previously:

Recommendation 6.

The guiding principles required to drive the program forward should include the following:

- **Be responsive to scientific discoveries by ongoing and new missions.**
- **Address science priorities as defined by the Decadal Survey and by MEPAG.**
- **Have missions build on each other both scientifically and technologically.**
- **Compete missions or payload elements to the extent possible within strategic direction.**
- **Inject a sufficient number of flight opportunities to sustain technical capability and to achieve steady progress on key goals; frequent missions may be essential to attracting the commercial sector and international partners.**
- **The choice of mission class should be determined by the specific science objectives.**

Rationale: These are straightforward principles that will help ensure that the Mars program is integrated into a single coherent *program.*

Recommendation 7.

The program should be sustained at a steady funding level, with commensurate results. The size and scope of the program—and, therefore, the progress that it can make—will depend on the resources provided.

Rationale: Having a steady funding level will ensure that mission planning and implementation can proceed without the inefficiencies that inherently result from uncertain funding and replanning associated with changing funding. Options for the size of the program are given in Section VI; clearly, the scientific results that can be obtained and the rate at which they are achieved will depend on the funding level.

Recommendation 8.

Utilize PI-led small spacecraft and Discovery-class and New-Frontiers-class missions, competed in a separate Mars Exploration Program line while addressing strategic goals.

Rationale: There are two points here. First is that for a Mars Exploration Program to be viable, it must develop science missions for flight; this is the way NASA makes scientific progress. Second is that it will be most productive for the program as a whole if the overall funding can support a range of mission sizes ranging from small spacecraft up through New Frontiers-class missions to be integrated into a viable program architecture. This means having the flexibility to accommodate missions with different development timelines and funding profiles. Note that we refer to Discovery and New Frontiers here only to provide a comparison point that will indicate the anticipated size/cost of missions. We are not suggesting that these Mars missions compete within those specific programs; in fact, we are suggesting exactly the opposite: that missions in these different classes be part of a single, separate Mars Exploration Program.

Recommendation 9.

The program should have a protected, adequately funded, and competed technology development program to advance instrumentation and developments in key areas (e.g., as has been done for the MAV). The technology invested should be focused and leveraged within NASA and with other agency and commercial entities.

Rationale: As our understanding of Mars advances, we recognize a need for new measurements and for different capabilities of platforms. These require advance development through a separately funded program in order to ensure that capabilities are available when they are needed. It is always tempting to reduce or eliminate funding for such technology-development programs when budgets get squeezed; this puts future programs at risk, so a protected program is necessary. We recognize, in addition, that many of the desired capabilities are not unique to Mars planning nor even other targets of NASA's planetary program; some development might be carried out elsewhere either within NASA or through commercial entities.

Recommendation 10.

With regard to technology development, a critical need for Mars exploration is that NASA develop low-cost approaches for entry vehicles at all size classes, including entry, descent, and landing.

Rationale: Continued exploration of Mars will require access to the surface by multiple lander or rover vehicles. At present costs, multiple entry vehicles of MER or PHX size class would be prohibitive, and there are no existing entry vehicles for the smaller spacecraft that still could carry out significant surface science. It is imperative for future Mars exploration that lower cost vehicles capable of delivering spacecraft that have substantial capability to the surface be developed. Entry vehicles from small spacecraft up through at least MER class are necessary.

Recommendation 11.

NASA should develop low-cost approaches for long-lived orbiting small spacecraft and for aerial vehicles, landers, and rovers to provide access and mobility after landing.

Rationale: Lower cost approaches to long-lived spacecraft have not been developed but are necessary for affordable Mars exploration and to take advantage of rapid technology evolution in this area. Consideration of making some of these craft long-lived does *not* mean imposing Flagship-class redundancy on such missions but rather developing low-cost approaches to risk mitigation, including through simulation, appropriate levels of testing, and possibly multiple craft.

Recommendation 12.

NASA and the Mars community should study the feasibility of adapting the CLPS program to Mars.

Rationale: A successful Mars-focused Commercial Mars Payload Services (CoMPS) could serve as a programmatic vehicle to allow, at reduced cost, development of technologies for future exploration, as well as delivery of specific science payloads. We recognize the issues here, in that 1) the CLPS program at the Moon, though promising, has not yet been demonstrated as successful; 2) Mars provides different challenges due to its distance and atmosphere, and 3) there would have to be enough potential flight opportunities to justify the necessary up-front investment from commercial entities. Thus, the recommendation here is to study the *feasibility* of implementing such a program.

Recommendation 13.

NASA and the Mars community should continue to explore, negotiate, and support international collaborations as a means of leveraging flight opportunities to achieve compelling science.

Rationale: Numerous examples exist in which international collaboration has allowed significant science to be carried out successfully (see Section IV.C). At the same time, there are counterexamples showing the difficulties that can arise. TGO is an example, in which NASA backed out of participation relatively late in the process (after selection of science instruments). In engaging in international collaboration, it is necessary that: 1) NASA involve the respective scientific communities in the definition and execution of joint missions; 2) to the extent possible, missions and instruments should be competed openly in order to get the best science; and 3) NASA-supported mission participants on non-NASA missions (Instrument Teams, Science Team members, Participating Scientists, Interdisciplinary Scientists) should be supported financially at adequate and appropriate levels to achieve the mission objectives.

Recommendation 14.

Adequately fund the analysis of returned mission data so results can be achieved in a timely fashion; support extended missions as long as they make solid scientific progress.

Rationale: Data that are not analyzed are data that may be lost to the scientific enterprise. Extended missions with their increased coverage in space and time have added to the information available for analysis and the opportunities for interdisciplinary study. Organization into new data products brings fresh insight to addressing fundamental questions about Mars and provides valuable feedback to the observational planning still in progress. Analysis of multiple data sets brings new understanding and more realistic testing of hypotheses and of model simulations. This takes effort, both in the analysis of data and the resulting formulation and testing of new hypotheses. Even with major advances in the handling of large data sets and in the tools for their analysis, funded researchers are the means by which the advances are made.

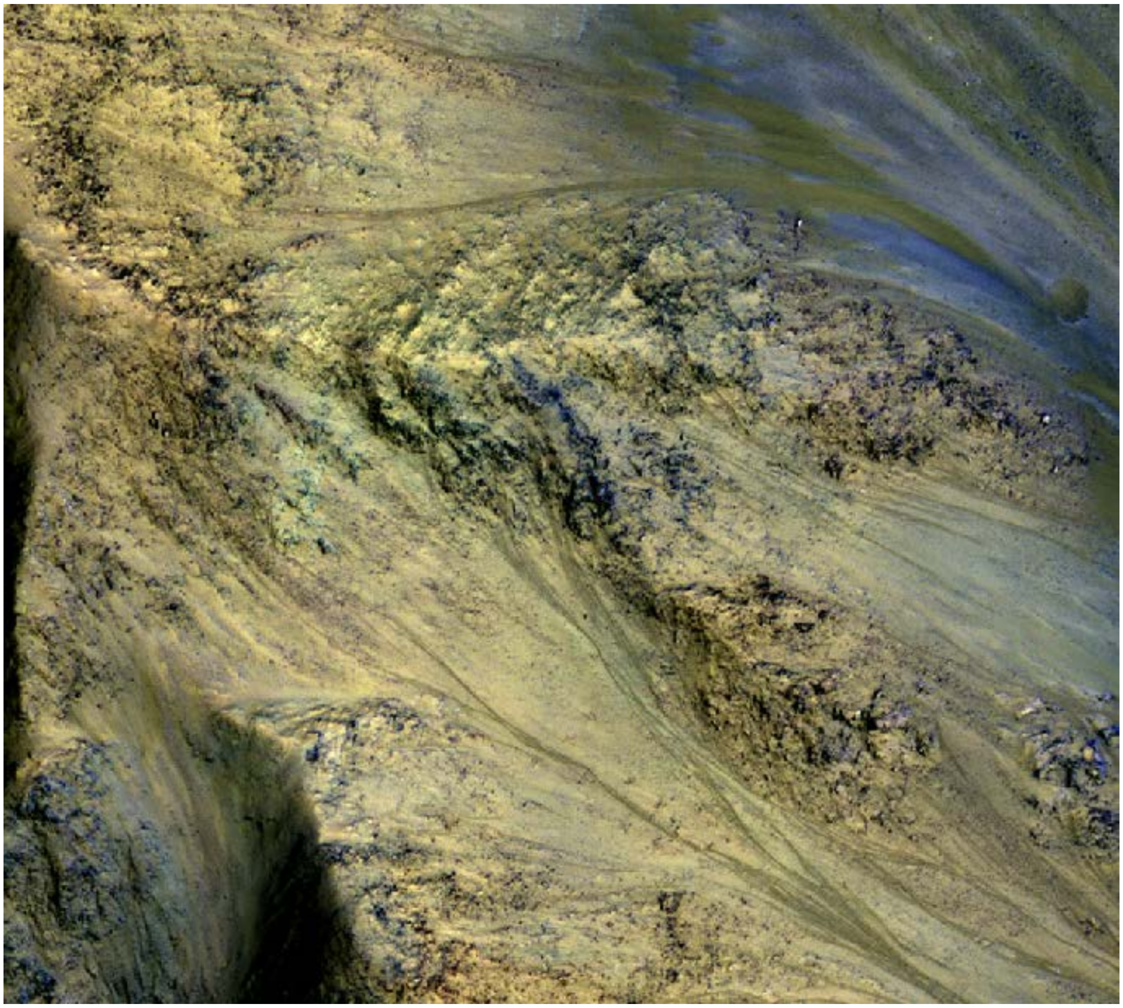
Spacecraft missions are perpetually at risk for having their budgets cut, and this tends to impact the science activities most severely. Some Mars missions have had their budgets cut even during their primary mission. Others have been funded in extended missions at a level that only allows data to be collected and archived but not analyzed. This throws the analysis burden onto the Research and Analysis (R&A) programs and decreases the likelihood of positive feedback on the data acquisition process. It also limits the involvement of the very experiment teams that best know their instruments and the potential of the data they produce. It is imperative that adequate funds be provided to ensure the reduction and analysis of spacecraft data in a timely manner. Deferment of analysis can lead to loss of science opportunities (for transient phenomena) or loss of personnel capable of carrying out data reduction and analysis (through retirements or transfers to other projects). That leads to fewer opportunities for new researchers to bring fresh perspectives to bear and for them to gain valuable flight experience. For all of these reasons, missions should continue to be extended after their primary missions and funded at adequate levels as long as they are doing valuable science or serving valuable programmatic functions; funding for extended missions must be built into budgetary planning.

Note that this is not a blanket push for all extended missions under all circumstances. Properly designed and implemented Senior Reviews would serve as a check.

Recommendation 15.

Enhance interactions between the revitalized Mars Exploration Program and the Human Exploration and Operations Mission Directorate (HEOMD) to define needs and the opportunities to address them.

Rationale: Given that one of NASA's long-term goals is to carry out human missions to Mars, it is necessary to have appropriate interactions and engagement between the human program and the Mars Exploration Program. Creating a formal group to oversee interactions would ensure that 1) adequate, accurate, and appropriate Mars knowledge and experience are provided in support of human missions, and 2) scientific progress will be sustained and advanced by missions with humans when they do fly. Robotic missions have lead times of 4–7 years, and follow-up to new discoveries must accommodate the 26-month cycle of the most fuel-efficient launches from Earth to Mars. Human missions are being planned to fly sometime in the 2030s; thus, interactions need to begin now, and missions that can support both the scientific and programmatic objectives need to appear in long-term planning now.



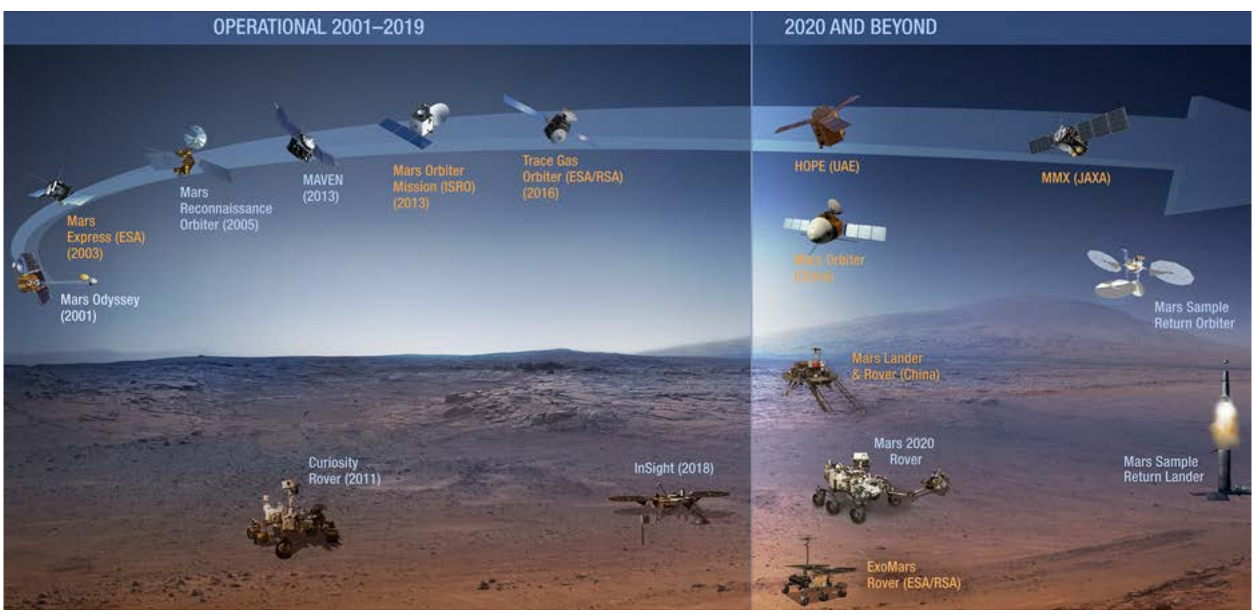
Recurring Slope Lineae (RSL) in eastern Valles Marineris: *Mars Reconnaissance Orbiter* (MRO) has observed these dark narrow streaks appear and lengthen down steep slopes during warm seasons, only to fade as surface temperatures decline seasonally. The RSL then recur in subsequent Mars years. Their nature has been much debated, with latest discussion favoring dry flows.
(Credit: HiRISE / U. Arizona / JPL / NASA)

VI. A Mars Program Architecture for 2020–2035

Mars exploration has long marched to the paradigm of global reconnaissance, *in situ* analysis, and sample return originally articulated in *An Exobiological Strategy for Mars Exploration* (NASA, 1995). Orbiters have searched for sites of particular interest (such as those with evidence for having had liquid water) and have put them into the global context of the evolution of Mars. Landers and rovers have examined specific sites *in situ* to test the understanding obtained from orbit, to explore in detail the physical and chemical evidence that is present at small physical scales, and to evaluate the potential ancient habitability of the sites by microbes. And, the MSR campaign, initiated with the launch of *Perseverance*, is the culmination of this effort so that carefully selected materials can be returned to Earth for study by the full range of Earth-science laboratory capabilities. Collectively, these approaches address all aspects of Mars science.

At the same time, and despite the successful missions to Mars by many nations, there remain unexplored terrains (e.g., *in situ* on the polar ice caps and in the subsurface), the challenge of investigating the amazing diversity of the surface environments recorded over the long history of Mars, and major outstanding questions about the history of Mars. The coverage in space and time of even the modern environment is incomplete at the level of detail needed to address these questions.

Here, we describe the missions that can take us, as an integrated program addressing the full range of Mars science, to the next level of understanding of Mars as a planet. We provide multiple options for "mission arcs" that could address different areas of science within an affordable program, while utilizing the full range of mission classes.



Left: Missions currently operating on Mars or in Mars Orbit.
Right: Mars Missions launched in 2020, currently in development or conceptual design. (Credit: NASA)

VI.A Mission Classes for Mars Exploration

To realize the scientific potential for understanding Mars, a Mars Exploration Program is needed to define a range of related science objectives; to invest and leverage technical developments in spacecraft, propulsion, and communications systems and scientific instrumentation; and to define risk approaches and development strategies that can achieve the needed reductions in mass and power while providing required capabilities, all at an affordable cost.

A salient principle is to break the science questions into discrete objectives and then to match them with an appropriate mission size or cost class. The current metric for flight missions has been Discovery-class (development costs capped at $500M, not including launch vehicle), New Frontiers-class (similar cap of $1B), and Flagship missions (> $1B). An exciting new development is the growing capabilities of small spacecraft (Section IV.B).

The term "small spacecraft" encompasses a wide range of concepts and can be defined in terms of mass, cost, or even deployment approach (e.g., rideshare). In this report, the emphasis is on the ability to achieve high-priority science at lower cost, a combination that can vary widely depending on the science objectives and observation requirements.

The ongoing rapid development of small-spacecraft capabilities has the potential to revolutionize Moon and Mars exploration by providing more affordable and more frequent flight of payloads for scientific exploration and for meeting human exploration needs. Extensive use of small spacecraft as part of a Mars Exploration Program is particularly appealing during an otherwise MSR-focused decade because such use could facilitate a complementary Mars Exploration Program that achieves high-priority science with frequent launches at an affordable program cost, thereby making substantial progress on key science questions and filling strategic knowledge gaps for missions with humans. That frequency may also open the way for commercial participation in providing needed services, particularly in the areas of how to get the instruments there and how to get the information back.

The cost, requirements, and performance relationships for small spacecraft focused on science have not yet been demonstrated in deep space or at Mars. The first round of planetary SIMPLEx missions is still in development, and other concepts generally have not yet flown. One small-spacecraft mission that is in process is the EMM *Hope*, currently in transit to Mars and scheduled to arrive in early 2021. At the cost for Phases A–D recently released publicly by the project manager, EMM falls within the range considered here for small-spacecraft missions. Orbiting small spacecraft seem within reach, but the ability of class D or single-string missions to observe over multiple Mars years is uncertain. Another critical need is to have missions in this class that can land on Mars with sufficiently capable payloads. PP and contamination issues will have to be addressed (see Appendix B).

Many science objectives will need to be addressed by the more capable Discovery- and New Frontiers-class missions. As discussed earlier, a Mars Exploration Program should strive to make best use of all mission classes by:

- Choosing missions in the appropriate size class while integrating them into coherent program lines that can achieve major science objectives;
- Set the requirements early and realistically on spacecraft size, capability, and longevity;
- Match the level of oversight to the mission complexity and the skill and experience of the team and partners;
- Develop and/or leverage key technical capabilities (e.g., smaller landers, long-lived small orbiters, scientific instrumentation); and
- Assist the process for transit to Mars, including early identification of rideshare

opportunities, and maintain the communications infrastructure needed to support data return, as these can be drivers to mission class.

VI.B Program Architecture: Perspectives and Possibilities—Mission Arcs

To demonstrate how a Mars Exploration Program could pursue compelling science objectives while utilizing a suite of missions, we have defined four "mission arcs" or mission-sequence scenarios; these are examples and do not encompass the entire range of compelling options. *Other mission arcs are certainly possible*, and the number and scale of arcs that can be pursued in parallel obviously depend on the available budget. A prime function of an ongoing Mars Exploration Program would be to work with the science community to define mission arcs actually to be implemented and to work issues of budget and schedule, including working with international and/or commercial partners. The point of the exercise here is to demonstrate that, although much still needs to be done technically and programmatically, important science can be achieved. Clearly, however, the pace of progress will depend on the funding level.

Tables VI-1 through VI-4 describe the four mission arcs presented here as proofs of concept. Each example identifies an area of compelling science, with a brief statement of goals and then a progression or choice of missions that would be strategically linked to achieve those goals. While there are many possibilities, the ones cited here are meant to demonstrate *that such strategically linked, compelling arcs can be defined*. Often, there is a three-phase progression from utilizing smaller missions to build on what is known today (e.g., diverse environments) to larger missions that would achieve ground-breaking progress. An effort is made to utilize lower-cost spacecraft early in the mission arc during a period when the next flight elements of the MSR campaign are projected to be in their development phases.

The increased capabilities called out later in the mission arcs are typically driven by the scientific objectives and the payload, as more complex measurements are needed to follow up earlier discoveries or to achieve more challenging science objectives (e.g., polar cap drilling). The proposed mission arcs here include both Discovery-class and New Frontiers-class missions to meet the more challenging objectives, and the program must have funding sufficient to utilize them if it is to succeed.

While individual missions could be competed through the small spacecraft or Discovery or New Frontiers processes, inclusion in an adequately funded strategic program line would ensure a consistent approach with missions building on one another (Section IV.A).

Note that while a mission arc typically focuses on a single theme or high-level objective, a single mission may contribute to more than one arc, and pursuing more than one arc in a timely fashion can enhance the return of both. That reflects the interdependency of processes in real environments and the value of contemporaneous and/or complementary measurements.

In Tables VI-1 through VI-4, as in Figure III-1, and in the discussion below, the mission classes are defined by:

- **SSc** denotes Small Spacecraft class.

  The life-cycle costs (*including* launch vehicle and Phase E ops/science) are taken to be in the range of \$100M–300M in FY20 dollars (Sections III and VI.A). There was considerable debate about this cost range. The SIMPLEx cost cap was viewed by many as being too restrictive to achieve compelling science in multiple missions across the mission arcs. That cap is ~\$55M without launch costs, which are included here. While one could argue that \$300M is really a low-cost Discovery-class mission, those missions would be competing against grander missions. Here, we envision a mission that is matched to a particular scientific focus within an integrated sequence of missions. Costs may drop as technology advances, but there are challenges of landing and functioning in extreme environments that still need to be met. Based on current trends, some small spacecraft missions could be closer to the lower bound, which would provide more opportunities when a program budget line is fixed.

- **DSc** and **NFc** describe missions having objectives and requiring resources similar to the Discovery and New Frontiers classes, respectively (Section VI.A).
- **FLG** describes a Flagship-class mission. We expect that missions at this scale would not be affordable until after the currently conceived MSR suite of missions has returned its samples to Earth, but advanced planning could proceed.

Table VI-1. Mission Arc #1: Diverse Ancient Environments & Habitability

Compelling Science	Explore diversity of ancient Mars, following up on the thousands of possible sites, to understand early planetary evolution and the nature, timing, and geochemistry of environments, habitability, and/or biological potential of Mars.
Goals	Quantify relative timing of major climatic / geologic / biochemical events and transitions in order to understand planetary evolution and biotic / prebiotic change.
Mission Arc	• **Phase 1**: High-spatial resolution mineralogy (≤ 6 m/pixel) from orbit to find best sites. – **SSc**: Mineral mapping by orbital spectroscopy. – **DSc**: Spectral and visual imaging from orbit. Synergistic with Arc #3. • **Phase 2**: Surface exploration of a subset of these environments with small landers. – **SSc**: Investigation of multiple sites using pinpoint landing, mobility (air, ground). – **Tech enabler: Affordable access to dozens of sites in the SSc**. • **Phase 3**: In-depth characterization of the most promising sites in terms of geochemistry, mineralogy, and biosignatures. – **NFc:** Detailed *in situ* imaging and spectroscopy, biogeochemical sampling and analysis, and age dating. – **FLG:** Life/biosignature analysis; 2nd MSR?

Table VI-2. Mission Arc #2: Subsurface Structure, Composition & Possible Life

Compelling Science	The subsurface of Mars is largely unexplored, and yet its structure and composition hold many clues to the early evolution of Mars. Further, it could be the refuge of an early Martian biosphere.
Goals	Explore the subsurface of Mars for water, chemical gradients, and signs of extant life.
Mission Arc	• **Phase 1**: Orbiter missions to 1) improve surface magnetism and gravity maps and 2) map ice structures and geomorphology beneath dust-covered terrains. – **SSC**: Low-altitude magnetic survey and gravity mapping. – **DSc/NFc**: Orbiter with surface / subsurface radar imager and sounder. Synergistic with ice science Arc #3. • **Phase 2**: Land electromagnetic sounders and active-source seismic devices at key surface locations from which to remotely probe subsurface structure, conductivity, and geochemical gradients. – **SSc/DSc**: Dedicated to landed remote EM sounding and active-source seismic devices; trace gas fluxes. – ***Tech enabler: Affordable access to multiple sites.*** • **Phase 3**: At most promising sites, drill / investigate to great depths, with *in situ* biogeochemical analysis. – **NFc/FLG**: Probe deeper at the most promising sites revealed in Phase 2. – ***Tech enabler: More advanced instrumentation, active devices, and drilling techniques.*** **Access to subsurface portals (e.g., caves, vents, cliffs).** – **NFc**: Prove out potential resources for *in situ* resource utilization (ISRU) by humans.

Table VI-3. Mission Arc #3: Ice—Geologically Recent Climate Change

Compelling Science	Understand Martian ice ages in terms of the distribution and stratification of ice as it was emplaced / removed over the last hundred million years, both in the polar regions and in lower latitudes.
Goals	*Climate Change*: Exploit the detailed record preserved in ice deposits, understand processes, and quantify relation to orbital cycles. *Biochemistry*: Seek evidence of past or extant life preserved in ice. *Resources*: Are there deposits suitable for supporting human activities on Mars?
Mission Arc	• **Phase 1**: Determine extent and stratification of near-surface ice across the planet from orbit. – **SSc**: Polar energy balance mission. – **DSc**: Synthetic aperture radar and radar sounding. Synergistic with subsurface Mission Arcs #1–2. *OR* – **NFc**: Combine radar and high-resolution stereo imaging, potentially with spectrometers for ice discrimination and thermal inertia (depth to ice); aids characterization of diverse sites (Arc #1) and exploration of subsurface (Arc #2). • **Phase 2**: Quantify drivers of ice emplacement / removal. – **DSc**: Landed imaging, shallow drilling / trenching, meteorology on polar cap and/or layered terrains. Complementary to low-latitude process field work (#4). • **Phase 3**: Observe and analyze detailed ice stratigraphy. – **NFc/FLG**: Landed imaging, deeper drilling, and meteorology on polar cap ice even in the polar night.

Table VI-4. Mission Arc #4: Atmospheric Processes and Climate Variability

Compelling Science	Record variability of the current climate from hours to decades and the processes of transport and photochemistry, Sun-Mars interactions, exchange of water, dust, CO_2 and trace gases.
Goals	*Climate*: Understand processes of climate evolution, including validation and improvement of models used to understand climate change over time. *Strategic Knowledge*: Provide environmental data for design and implementation of robotic and human missions.
Mission Arc	• **Phase 1**: Climate Variability & Strategic Knowledge – **SSc**: Multiple, long-lived SSc to achieve global and local time coverage (e.g., areostationary), and long-term records of temperature/pressure, winds, and aerosols and water (columns and profiles). ***Tech enabler*: *Long-lived small spacecraft.*** – **DSc**: Multiple measurements on one spacecraft, including active sensors (e.g., lidar for winds, aerosols). Support for SSc constellation. • **Phase 2**: Improve understanding of climate processes (non-polar ice); complement ice landed missions (Arc #3). – **DSc**: Intensive 1–2 non-polar field campaigns to understand dust storm onset, water vapor and momentum exchange, and trace gas transfer. • **Phase 3**: Understand boundary layer/surface exchange – **NFc**: Network of landed stations to profile boundary layer fields and measure near-surface fluxes across Mars. (Measurements should be simultaneous with fields measured by small satellites.)

VI.B.1 Mission Arc #1: Diverse Ancient Environments and Habitability

A major and compelling result of the MEX and MRO missions is the discovery of widespread and ubiquitous alteration of ancient Noachian crust (Ehlmann & Edwards, 2014). Early stratigraphic sequences comprise a rich and diverse record of aqueous environmental conditions that largely ceased after the first 1–2 billion years. CRISM and OMEGA data combined with constraints on stratigraphy from HiRISE indicate nearly a dozen distinct, habitable aqueous environments (e.g., Murchie et al. [2009], and many subsequent studies). Based on stratigraphy and crater densities, these trace the climatic evolution of early Mars. Yet, the nature, duration, and drivers of major environmental transitions are still unclear, as is how these transitions may have affected the habitability of surface and subsurface environments and whether these environments were ever actually inhabited.

Unlocking the geologic sequence stratigraphy of these transitions through time is crucial to interpreting the history of this dynamic and changing period on early Mars, as well as understanding how early solar, impact, and interior processes drive the evolution of habitable rocky planets generally (Ehlmann et al., 2016). This requires detailed investigation of many diverse environments.

To date, instrumented rovers have visited only four locations, with three or more to be added in the next several years if successful. These locations represent only a small fraction of the thousands of possible sites that have been identified from orbit that can help define early planetary evolution, and the nature, timing, and geochemistry of environments, habitability, and biological potential of Mars. Thus, more needs to be done from orbit, together with *in situ* investigations at multiple, carefully chosen sites.

Extended coverage at better spatial resolution is key to understanding the record retained in these early aqueous environments, via the distribution and abundance of alteration phases as well as their geologic implications. Current spatial resolution and coverage at the near-infrared wavelengths of greatest interest are from OMEGA and CRISM (globally at ≥ 200 m/pixel) and from CRISM (~ 18 m/pixel, but only for a carefully targeted ~2% of the planet).

The improvements in spatial and spectral resolution and capability in going from the MGS Thermal Emission Spectrometer (TES) to the Mars Odyssey Thermal Emission Imaging System (THEMIS), from MEX OMEGA to MRO CRISM, and from the Viking Orbiter cameras to the MGS Mars Orbiter Narrow-Angle Camera (MOC) to MRO HiRISE, all have illustrated that such improvements lead to major new discoveries.

To address these goals, Phase 1 in this mission arc is to improve on orbital mineral mapping of environmental transitions. This can readily be accomplished using an SSc orbiter with instruments that are in development for future launch opportunities (e.g., imaging spectrometers or multispectral imagers similar to Polar Radiant Energy in the Far Infrared Experiment (PREFIRE) for Earth Ventures or Lunar Trailblazer/HVM[3] for SIMPLEx). Within a DSc mission, additional instruments such as even higher resolution imagery or improved spectral fidelity in the long-wave infrared could be included. This phase and its instrumentation would have synergies with mission Arc #3, where spectral instruments are used to map surface ice composition or determine ground thermal inertia.

Phase 2 would be the true game changer, as it would require affordable access to multiple sites on the ground in order to explore the true diversity reflected in the enhanced orbital data (Ehlmann et al., 2016). As mission costs have crept upward, access to the Martian surface is currently barely affordable in New Frontiers for mobile systems, and even fixed landers need significant reuse of hardware or international contributions to fit within Discovery.

This second phase requires technology development that leads to affordable surface access with mobility, either by rovers or aerial platforms (Finding 7 in Section III and Recommendation 5 in Section V). Multiple small platforms, perhaps delivered and supported by a single "mother ship," may be essential to make further progress in landed science.

Having characterized numerous sites spanning a range of geochemical settings, Phase 3 would follow up with additional detailed analysis *in situ* or deep drilling at the most promising site. *In situ* isotopic analyses and age dating could further revolutionize our understanding of the geologic timeline and staging of events that are currently only constrained by impact crater density and qualitative measures for visual weathering and erosion. Current studies suggest these may require larger landed platforms that are presently NFc class or even larger.

We can also envision a potential second MSR in the mid-2030s, where the samples from the new site would broaden what was learned from samples collected in the current MSR campaign, would investigate additional environments for biosignatures based on new *in sit*u analyses, and/or characterize / certify the best site for future *in situ* exploration by astronauts on the ground.

VI.B.2 Mission Arc #2: Subsurface Habitability and Possible Life

Better orbital data and innovative rover observations at the surface have established the past existence of dynamic and long-lived subsurface aqueous systems on early Mars. There also is the tantalizing suggestion that liquid (briny) water may exist 1.5 km below the ice cap near the southern pole of Mars (Orosei et al., 2018), raising the possibility that subsurface liquid water exists today, albeit at depth, and that more ice deposits could be detected with advances in sensing technology.

The structure, architecture, and composition of the Martian crust hold many clues to the early evolution of Mars, and its volatile reservoirs record geologically young climatic variations. In addition to achieving major scientific advances, this effort would gather fundamental information for future ISRU.

Lastly, telescopic, orbital, and rover observations have pointed to the possibility of the release of methane gas on a range of spatial and temporal scales. The origin and nature of such exhalations is a prime target for subsurface exploration. If life ever got started on Mars, the subsurface could be the present-day refuge of an earlier Martian biosphere. *The possibility of detecting extant life in the Martian subsurface is a major driver of this arc.*

Apart from radar soundings of the polar caps and limited areas of the mid-latitudes, the subsurface of Mars is almost completely unexplored, with inferences of subsurface structure and architecture from orbital radar imagery, visual topography, and gravity providing the most data. Only one mission, InSight, has been fully dedicated to exploring the interior seismicity and heat flow. While InSight will open up analyses to this third dimension, challenges to the progress of its thermal probe and to the analysis of data from a single seismic station will limit what can be learned.

To go beyond global-scale geophysics will require different instrumentation. While the detection of extant subsurface life has its challenges, a place to start is to determine where water may be present and where there are biologically relevant energy sources.

The goal of this arc is to "follow the water" at depth, along with trace gas fluxes from the subsurface. The three-phase approach to this arc would be: 1) regional to global surveys from orbit, 2) distributed reconnaissance landers (likely with EM sounders), and 3) robust, deep drilling to different depths.

<u>Phase 1</u> of this mission arc consists of orbiter missions to improve maps of surface magnetism and gravity and to obtain maps of ice structures and geomorphology beneath dust-covered terrains. Our best knowledge of the magnetic field is limited to magnetometer measurements taken on low-altitude passes of the Mars Global Surveyor through the upper atmosphere during its orbit insertion and aerobraking phase, complemented by spatially limited resolution data from MAVEN.

Gravity, currently derived from spacecraft tracking using their communications systems, would benefit dramatically from a Gravity Recovery and Interior Laboratory (GRAIL)-like mission, especially if sensitivity to deep water could be achieved. Mapping near-surface ice deposits, another essential step, can be accomplished with a DSc or NFc class orbiter with imaging and sounding radar as well as complementary visible imaging. Such a mission would be entirely synergistic with Mission Arc #3 for Ice Science.

In Phase 2, reconnaissance from Phase 1, integrated with past measurements, would identify key surface locations with promising characteristics for probing subsurface structure, conductivity, and geochemical gradients.

As we have only very limited knowledge of how orbital data translates to subsurface characteristics, strategic analyses of several promising sites are required in order to build expertise and knowledge to follow up with larger efforts. This phase can be accomplished with SSc and/or DSc missions dedicated to landed remote electromagnetic sounding, ground-penetrating radar, and active-source seismic devices best done at multiple sites.

If orbital sensitivity to deep water or brines is not forthcoming, it may be best to focus from the start on technology development of small landers that could be deployed at several sites to measure trace-gas fluxes and to use EM sounding to identify local subsurface water. To investigate the biological potential of shallow ice, a more sophisticated DSc lander might be chosen in this phase.

From Phases 1 and 2, promising options will be identified for the most ambitious and costly phase of the arc. In Phase 3, the objectives are to investigate to great depths, possibly via drilling with *in situ* biogeochemical analysis. This may require a larger mission class, NFc or FLG, to probe deeply with advanced drilling techniques and instrumentation for chemical and gas analysis.

VI.B.3 Mission Arc #3: Ice Mapping and Geologically Recent Climate Change

A major discovery of recent Mars missions is the prevalence of near-surface ground ice, as seen, for example, in MRO SHARAD radar returns (e.g., Bramson et al. [2015]), HiRISE images of steep cliff faces exposing thick layers of dense ice (Dundas et al., 2018), and ice exposed by new impact craters (Dundas et al., 2014). In addition, stratigraphy in the polar layered deposits (PLD) has been linked to recent and longer-term obliquity variations (e.g., Smith et al. [2020]).

Thus, this mission arc is focused on recent climate change as recorded in surface and subsurface ice deposits. It seeks to understand Martian ice ages in terms of the distribution and stratification of ice as it was emplaced and removed over the last hundred million years, both in the polar regions and in lower latitudes.

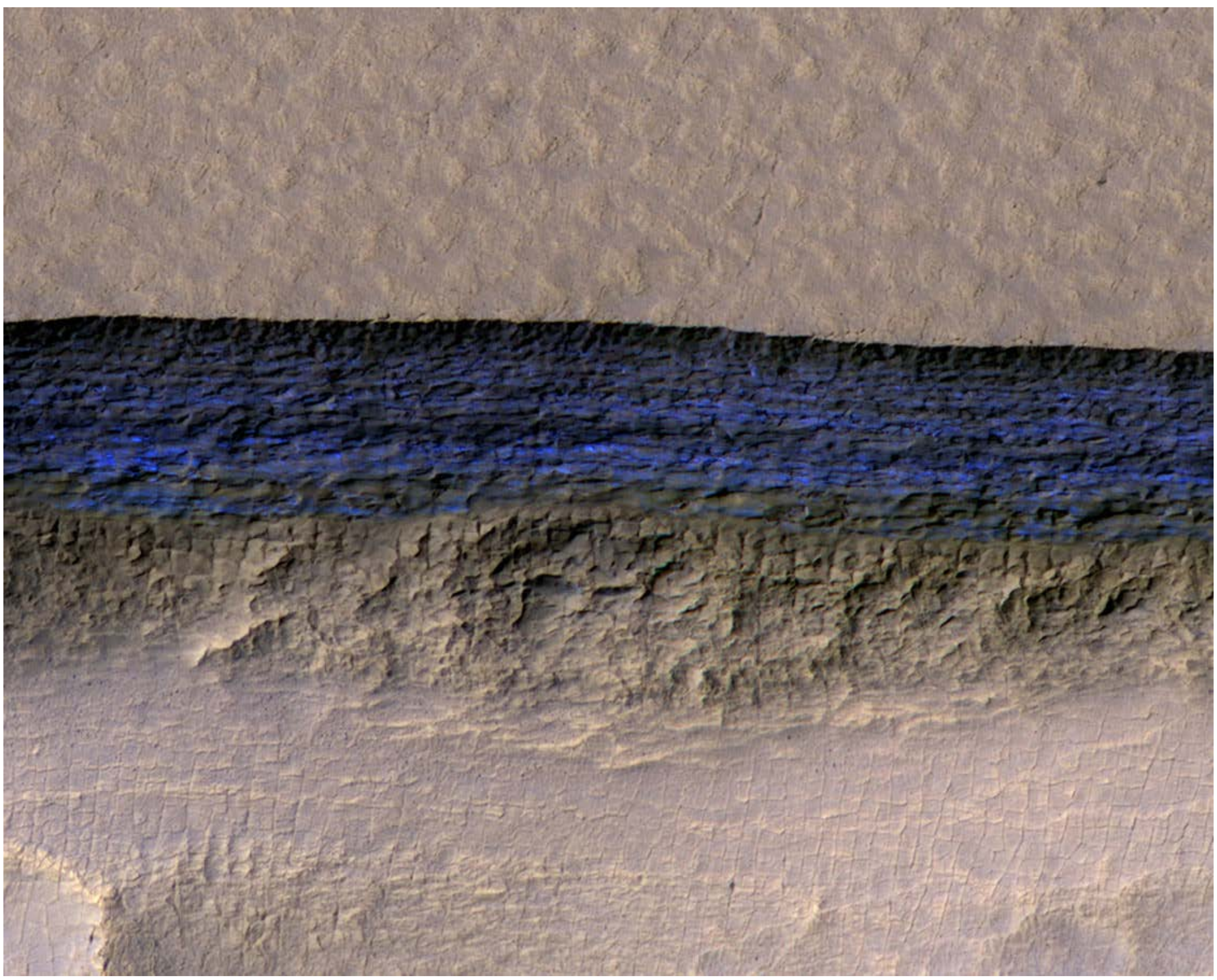
Understanding the climate record retained in ground-ice reservoirs requires better observational constraints on the lateral extent and volume of ice, as well as the depth to the top of the ice table at low latitudes where ice is expected to be buried under several meters of dry overburden. The recent detection of massive ice there, rather than simply pore-filling ice, challenges current thermal models that predict any near-surface ice should be geologically young and actively retreating in the current climate (Bramson et al., 2017).

In the polar regions, while coarse internal stratigraphy is observed in radar sounding data of the PLD, the scale of layers seen in MOC, HiRISE and Context Camera (CTX) imagery is much finer, and the link between radar layering and imagery layering remains unclear. Major unknowns regarding the climate history recorded in the PLD include the time span recorded in the PLD (possibly different between north and south by an order of magnitude or more), the completeness of the record, and the temporal resolution in individual layers.

To take the next step, we need to understand the processes that form and remove ice strata in the mid-latitudes and the poles, as well as to quantify the relationship between that stratigraphy and the history of obliquity cycles (MEPAG ICE-SAG Final Report, 2019).

To address these goals, Phase 1 exploration in this mission arc is to determine the extent and stratification of near-surface ice across the planet from orbit. Depending on funding availability, this phase could begin with a small orbiter (SSc) dedicated to observing the current polar energy balance as a means to determine whether and where net annual deposition or net erosion is occurring in the PLD. This would be followed by orbital radar imaging and sounding at higher frequencies than the current sounders, MEX MARSIS and MRO SHARAD. The goals of this investigation can realistically be accomplished in a DSc mission that also would have synergies with subsurface science goals in mission Arcs #1 and #2. In addition, this phase can address whether there are near-surface ice deposits suitable for supporting future human activities. An enhanced New Frontiers class NFc mission would add thermal-infrared observations to determine surface thermal inertia related to the depth to the shallowest (< 1 m deep) ground ice and short-wave infrared spectroscopy to map water-ice composition of the PLD exposures at higher resolution than CRISM. These spectrometers also could map surface mineral compositions, a major goal of mission Arc #1.

Phase 2 is intended to quantify drivers of ice emplacement and removal. This involves landed science to measure the fluxes of water, carbon dioxide, and dust as well as the seasonal and annual processes resulting in layer formation at the poles or transport into and out of the mid-latitude regolith. Measurements would include comprehensive meteorology that has synergies with Mission Arc #4, or shallow drilling or trenching in order to measure the



HiRISE view of water-ice (blue in the above color-stretched image) exposed in a cliff in high southern latitudes (NASA Credit: MRO / HiRISE / U. Arizona / USGS / JPL / NASA) fine-scale vertical structure in polar or mid-latitude ice.

Of particular interest is the measurement of isotopic ratios, especially D/H, which is known to vary seasonally in both the lower and upper atmosphere (e.g., Villanueva et al. [2015], Clarke et al. [2019]). The relationship of its atmospheric signature to polar and mid-latitude ice reservoirs would provide compelling links between the ice stratigraphy and past climate epochs (Jakosky, review in press). It is notable that, of the early failures of Mars Observer, Mars Climate Orbiter, and Mars Polar Lander, only from the last—a small mission to land on and trench into polar layered terrain—has the science *not* been recovered by subsequent missions. This arc would fill that void.

Phase 3 of this arc builds on preceding analyses with orbital observations and landed assessment of the detailed ice stratigraphy. This large-scale NFc or FLG mission would involve landed observation of ice stratigraphy, deeper drilling than in the prior phase, and perhaps meteorology on the polar-cap ice throughout the full annual cycle (including the frigid polar night) to characterize the deposition and erosion of the seasonal CO_2 ice layer. Such a mission could truly revolutionize our understanding of the Martian climate system and habitability.

Water is the key to habitability on Mars, and as such, ice reservoirs are an important potential preserver of either extant or extinct life. Microbial life is known to exist in a wide range of frozen terrestrial habitats (Boetius et al., 2015), so ice reservoirs are one possible refugia if life ever got started on Mars. Broader goals for the Mars program related to ancient habitability and subsurface exploration (Mission Arcs #1 and #2) are synergistic with the deep ice drilling and subsurface exploration that is the end phase of this mission arc. Technologies to achieve this would have application to other icy worlds.

VI.B.4 Mission Arc #4: Atmospheric Processes and Climate Variability

The last 20 years have seen significant advances in our knowledge of the Martian atmosphere and climate system. However, fundamental gaps in our understanding remain that require additional observations to resolve.

This mission arc seeks to better characterize the controlling processes and the state of the present-day Martian climate in response to modern drivers. An understanding of these processes can then be used to extrapolate into the past when driving conditions and atmospheric composition may have been different.

A test of that understanding is the ability to simulate the modern climate and its variability over a range of timescales, from hours to decades or longer. In that way, a knowledge of the basic transport processes associated with aerosols, volatiles, and trace gases provides a means for understanding Mars' climate throughout its history. Such an emphasis would also naturally include the basic seasonal cycles of dust, CO_2, and H_2O, but also photochemistry, atmospheric boundary layer exchanges with the surface, Sun-Mars interactions, and the validation and improvement of models used to investigate climate change over time.

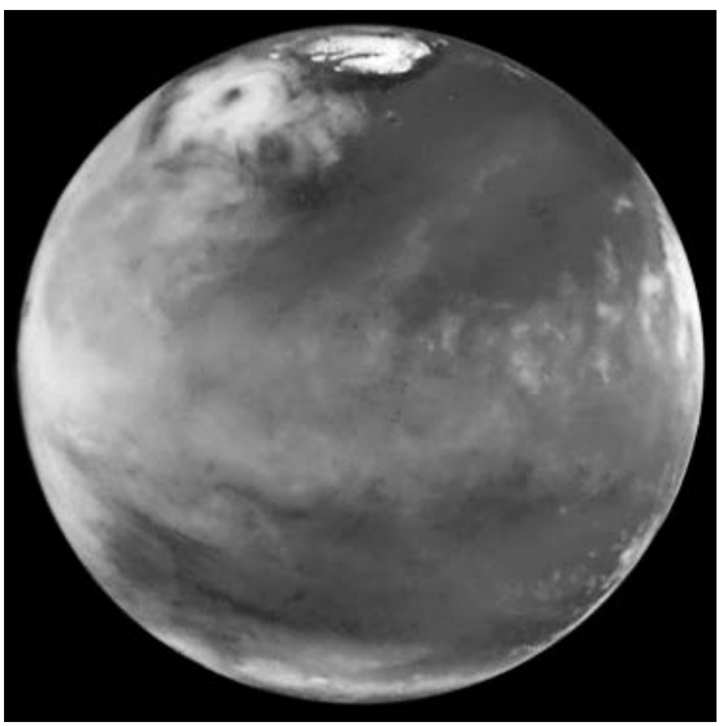
Although measurements of atmospheric aerosols, temperature, and column water vapor have been made for several Mars years (Haberle et al., 2017), atmospheric studies have lacked the necessary combination of coverage, temporal, and spatial scaling needed to more systematically address transport processes and climate variability. Winds and water vapor vertical distributions have not been measured extensively, and profiling of near-surface fields and exchanges with the surface are woefully lacking. A compelling set of missions could acquire the data needed to investigate the main scientific questions.

As with other mission arcs presented here, the collection of missions needed to make progress is organized into three phases, with the full mission arc intended to address the following program elements:

- Orbit-based characterization of atmospheric circulation and of transport processes.
- Transport of aerosols and their relationship to atmospheric spatial/temporal scales and to climate.
- (*In-situ*) surface-atmosphere boundary layer interactions (e.g., water vapor and other trace gas measurements).
- Acquisition of strategic knowledge, in the form of environmental data for design and implementation of robotic and human missions.

In Phase 1, knowledge gaps are addressed by a set of multiple SSc, or perhaps more efficiently by a combination with a DSc. Recent technical developments should enable small orbiters to provide global spatial and diurnal local time coverage (e.g., with some in an areostationary orbit) with current instrumentation. (The just-launched EMM *Hope* mission may be a start to this.) The observation goal would be long-term global records of temperature/pressure, winds, and both column and vertical profiles of aerosols and water vapor. Because the durability of SSc is not yet proven for the Martian environment, these missions would benefit from a program aimed at achieving long life for small orbiters. These capabilities could be augmented with a DSc orbiter carrying an integrated payload including new remote sensors, e.g., active systems, such as lidar for winds and aerosols, submillimeter for temperature profiles, water vapor profiling, and middle-atmosphere winds even in the presence of aerosols (MEPAG NEX-SAG Report, 2015).

In Phase 2, landed missions would investigate exchanges of the atmospheric boundary layer with the subsurface and the deeper atmosphere with either one or two intensive non-polar field campaigns. Emphasis is on the complement of instruments needed to understand the onset of dust storms, the interplay of water



The Mars atmosphere today: A large cyclonic storm is seen near the north polar ice cap, while the aphelion water-ice cloud belt is prominent across the low latitudes (middle of image).

vapor and momentum exchange, and trace-gas interactions between the surface and atmosphere. The implementation could be based on a DSc landed platform designed to make the proper measurements *in situ* (including from unobstructed masts) and through up-looking remote sensing. A key is to operate continuously while making high-frequency measurements. This phase would be complementary to measurements in Arc #3 at a polar site.

Because of the tightly coupled and nonlinear nature of the Mars climate system, the biggest leap forward in our understanding of climate processes will ultimately come from conducting multiple observations from landed platforms across the Mars surface simultaneously with orbital remote sensing, as is done on Earth.

In Phase 3, the mission arc therefore culminates with a network of landed stations, with a funding profile commensurate with a New-Frontiers-class mission. The collection of platforms would be tasked with profiling boundary layer quantities (e.g., winds, aerosols, temperatures) and with the measurement of near-surface dynamical fluxes in a variety of terrain types on Mars. Ideally, the long-term SSc orbital constellation of Phase 1 would provide the remote sensing needed to characterize the general circulation as it influences the region around each of the stations.

Ultimately, this network could evolve to provide the routine meteorological information needed to support activities by human explorers operating on the surface of the planet. It would do so both by providing the environmental data needed to design shelters, power sources and other facilities and by providing the initial elements of a monitoring network advisable to support surface operations by humans in an efficient and safe manner.

VI.C Program Scope and Affordability

Table VI-5 shows the possible number of missions in each of the proof-of-concept mission arcs. These are not based on any detailed study but are meant to provide some idea of scope if two or more of the mission arcs were to be pursued.

In Table VI-5, the following rough order-of-magnitude costs were arbitrarily assigned: \$200M for SSc, \$750M for DSc, \$1250M for NFc. Important assumptions include:

- The numbers in FY20 \$M are meant to be a representative average. No attempt was made at year-by-year cost profiles and no inflation was computed;
- Costs notionally include launch vehicle / rideshare and prime mission Phase E;
- The numbers do not reflect possible international contributions or commercial partnerships;
- Flagship-class mission launches were assumed to occur after 2035;
- Costs for missions extended beyond their prime mission together with instrument and spacecraft technology advances could add \$150M a year or more; and
- No costs needed to complete the MSR campaign are included here, including costs to analyze, curate, and archive the returned samples.

The number of missions to be launched may appear daunting, but reflects the progress possible with small spacecraft. The Program is likely to have to make choices between mission arcs. MASWG strongly recommends that progress be implemented on at least two arcs, interleaving missions as appropriate. Two DSc missions in the next 10 years is a reasonable goal, with one or more NFc in the 15-year period envisioned here.

As for the large number of SSc, it should be noted that, for both Arcs #1 and #4, many of the small spacecraft are envisioned to have essentially the same payload to be delivered into different orbits or at many different landing sites. In those cases, several may be developed and launched in the same opportunity.

Programmatic coordination of small launch opportunity acquisition or early identification

Table VI-5. Mission numbers for the various mission arcs described in Section VI.B and Tables VI.1–4. Costs were roughly estimated assuming (on average) $200M for SSc, $750M for DSc, and $1250M for NFc mission classes. The programmatic support line is specific to these mission arcs; it does not include current R&A, extension of current missions (including *Perseverance*), or costs associated with handling and analysis of samples returned by the MSR campaign.

TABLE VI-5: Mission Arcs & Program Scope			
Mission Arc	**2021-2030**	**2031-2035**	**Key Technology**
Arc 1: Diverse Environments	4 SSC, 1 DSc	1 NFc, 1 SSc	Small Landers
Arc 2: Subsurface Habitability	1 SSC, 1 DSc	1 DSc, 1 NFc	Drilling, In Situ Analysis
Arc 3: Ice Science	1 SSC, 1 DSc	1 DSc, 1 NFc	Ice Landers
Arc 4: Climate Variability and Processes	4 SSC, 1 DSc	1 SSc, 1 NFc	Long-lived SSc, Network Landers
Assuming Progress on several Arcs	~$300M / yr (8 SSc, 2 DSc)	$500M / yr (2 SSc, DSc, NFc)	
Assuming Progress ~2 Arcs	~$150M / yr (4 SSc, 1 DSc)	$300M / yr (SSC + NFc or 3 SSC + DFc)	
Programmatic Support: Technology, Extended Missions, Instruments, Data Analysis	$150M / yr (additional)	$150M / yr (additional)	Key: Affordable access to the Mars surface

Note: Mission cost assumptions in this document are of a budgetary and planning nature and are intended for informational purposes only. They do not constitute a commitment by NASA.

and coordination of rideshare opportunities with NASA, international, and commercial entities is crucial.

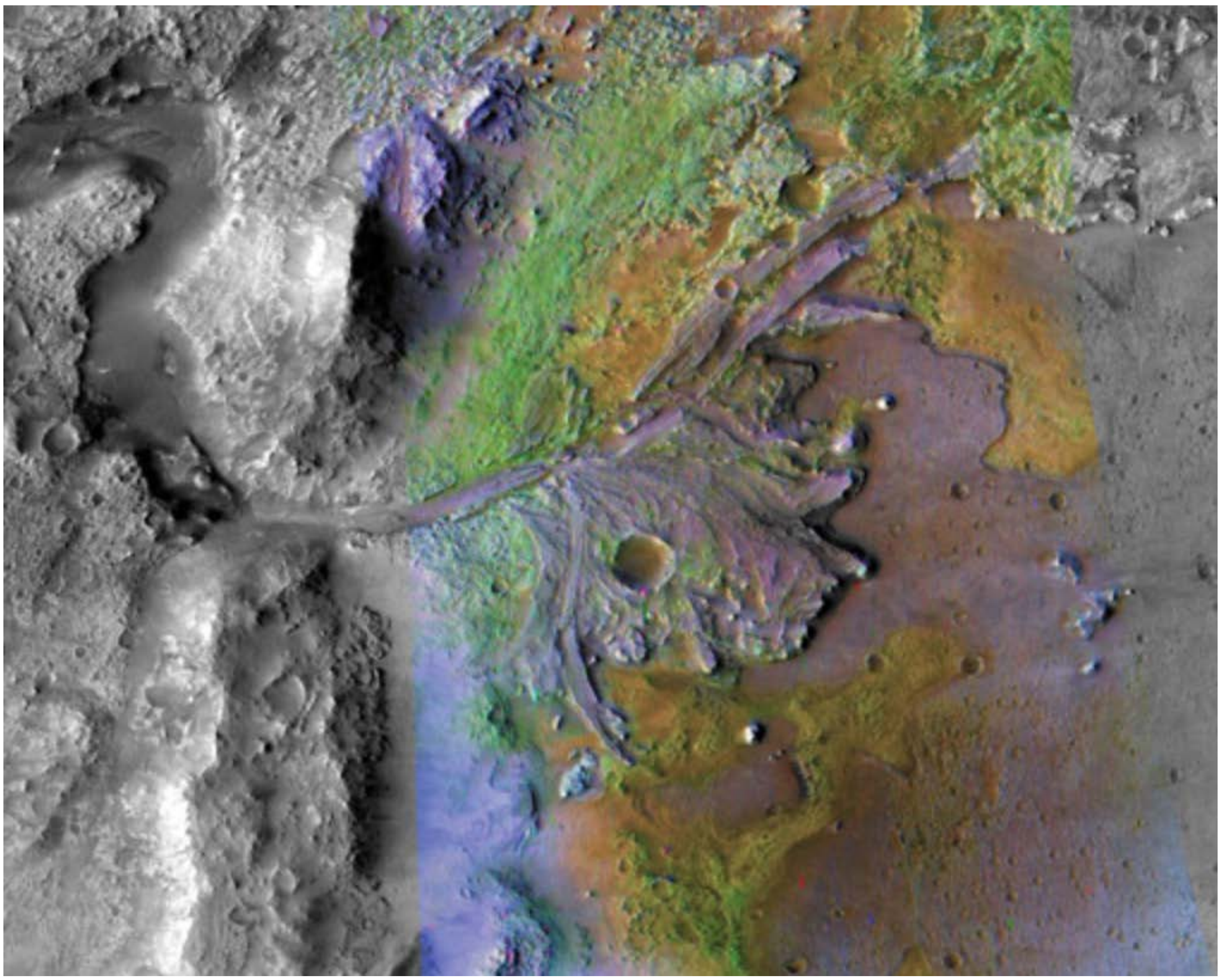
With regard to technology development, a key function of the program would be to pursue new developments in partnership with other NASA elements and/or international space agencies. For example, there could be some crossover when developing technologies for exploring the Mars polar caps and mid-latitude ice and the icy satellites of the outer planets.

As stated in the assumptions above, the funding for this exploration would be in addition to that needed to finish MSR. The next Mars flagships are likely to be driven at least in part by the scientific yield of the analysis of the returned samples.

The funding for making major progress while the MSR campaign is proceeding is comparable to the recent non-MSR components of the Mars Exploration Program.

To minimize the impact on the breadth of planetary science that NASA seeks to do other than at Mars, the required funding for this part of the Mars Exploration Program would need to be added to the Planetary Sciences Division budget. The balance between exploration of Mars and of the rest of the solar system clearly depends on that budget.

However, there is much that we need to learn about Mars, and Mars preserves the clues of a long and fascinating history. The answers are there, exceptionally accessible to our robotic missions and, ultimately, to humans operating safely on its surface.



Deltaic formation in Jezero Crater, the target for the *Perseverance* rover landing on Mars in February 2021. This false color image indicates different minerals, some produced by the action of water (e.g., green implies carbonate material).
(NASA Credit: CRISM / JHUAPL / JPL)

VII. Implementing a Mars Exploration Program

Compelling scientific, programmatic, and technological arguments exist for NASA to support a vigorous and robust Mars program that operates in addition to, and in parallel with, the Mars Sample Return (MSR) program.

In concert with the recommendations of *Visions and Voyages*, MSR should proceed, as it is the single effort at this time most likely to produce a major step forward in our understanding of Mars. The analysis of returned samples will have major implications for science and for both robotic and human exploration missions to be launched in the 2030s and beyond. The recent launch of *Perseverance*, which will prepare a cache of carefully selected and documented samples for future return, is a giant step forward in this endeavor. *To address the remaining scientific objectives requires additional flight missions as part of a program.*

Scientifically, Mars provides the best opportunity to understand the development and evolution of an Earth-like planet. Most of the processes and properties on terrestrial planets, including interactions between geological, geophysical, climate/atmosphere, space weather, and potential biological processes, can be viewed on Mars today or interpreted from the physical and chemical records of past environments. Among the solar system's planets, including Earth, Mars has the best-exposed and best-preserved 4-billion-year physical record. Sample return from the Jezero Crater environs will provide a major contribution to interpreting that record, but *in situ* observations at other sites across the planet and their analysis are required to answer fully the major questions of climate change and possible life origin on a complex body that we now know to have been habitable; i.e., one that has the necessary ingredients for life.

Programmatically, Mars is accessible: By comparison to other planets, trip times are short, and the surface environment is relatively benign. Mars is the logical next destination for humans to explore beyond the Earth-Moon system. The value of infrastructure and synergistic observations from orbiters, landers, and rovers has been demonstrated, both for mission safety and for mission science, by the ongoing Mars Exploration Program. The question is how to build on past success.

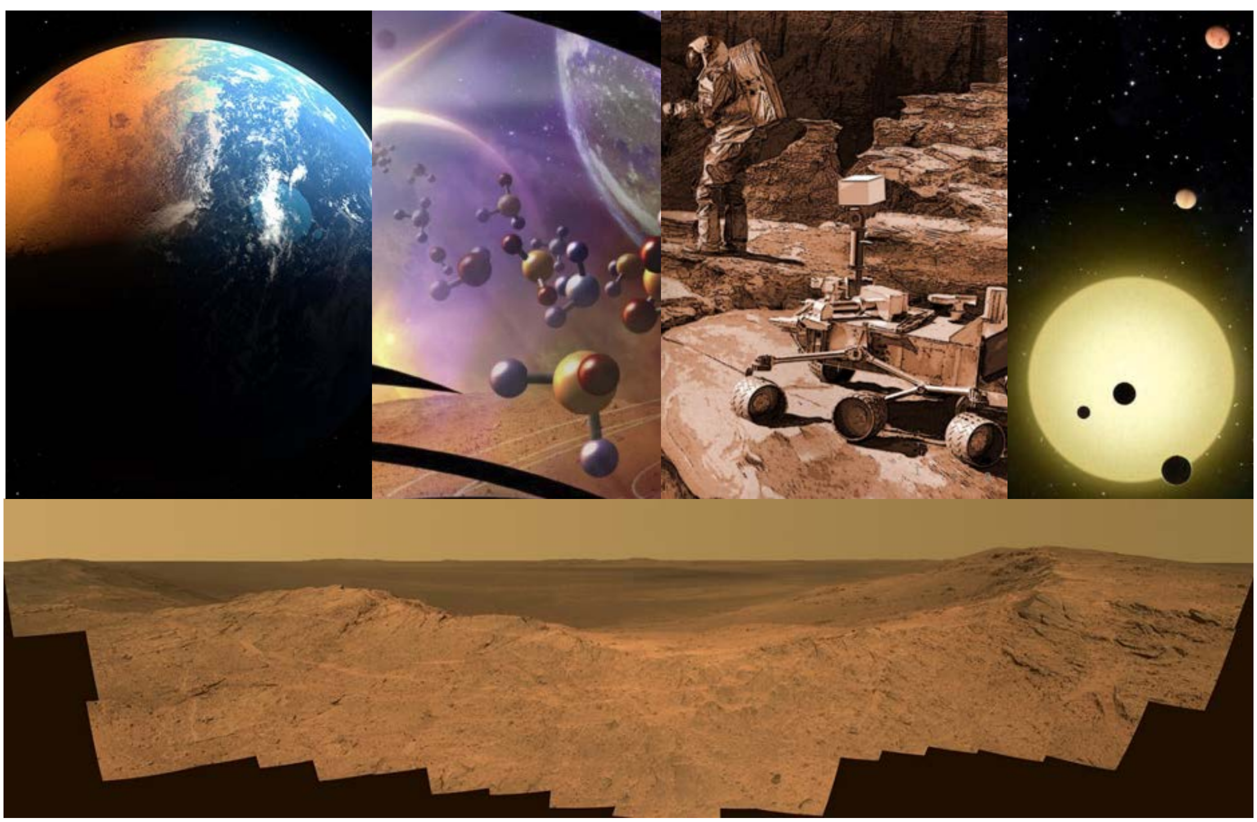
The challenge is how to explore Mars during a period when MSR and exciting non-Mars missions will strain the current planetary science budget. International partnering, as is being done for MSR, is one means of achieving what needs to be done, through partnerships that can leverage costs across multiple partners. Commercial entities have already helped reduce launch costs, and particular companies have expressed interest in providing essential services for Mars exploration. Ongoing developments in lunar exploration and the growing number of space agencies sending missions to Mars may lead the way for future collaborations, but these will require nurturing and possibly new business models for the challenges inherent in Mars exploration.

One new development that should be exploitable early on is the ongoing rapid development in small-spacecraft capabilities. Their application to remote sensing from orbit is already under study, and a critical development would be to show their ability to bring significant science to the surface at much lower cost than at present. The use of lower-cost missions early on would help maintain progress on important scientific questions during the development of those flight missions needed to return samples cached by *Perseverance*.

More capable missions (Discovery-class, New Frontiers-class and eventually Flagship-class missions again) will be needed to address the most challenging objectives and discoveries. All would benefit from a robust communications infrastructure and advanced technology that could augment data return and reduce landing costs while improving landing precision.

To pull all this together will require a continuing Mars Exploration Program, adequately funded and sufficiently independent so that missions can be selected within a long-term vision of the science to be accomplished and the programmatic goals. Such a program would work with the science community to decide the mission arcs to be pursued, to seed the technology investment needed to pursue that science affordably, to work with international and commercial partners, and to work with the human exploration program to acquire useful knowledge and flight experience, while building the infrastructure required for implementing missions with humans.

This program would need the independence and access to science provided through the Science Mission Directorate and its Planetary Science Division. Where this leads in terms of future organizational structure is a subject for the future, especially should the national program of exploring Mars with humans on the planet come into better focus. However, it is not too early to pursue the compelling science questions robotically while helping to enable and shape the best use of future human activity on Mars to answer the fundamental questions about Mars and what it can tell us about the other terrestrial planets, including Earth, and planets beyond our solar system.



Appendices

Sunset on Mars as observed from the *Spirit* Mars Exploration Rover. (Credit: NASA)

Appendix A MASWG Meetings and Activities

MASWG utilized several opportunities to collect input from specific projects and on specific topics, to obtain input from the community, and to solicit feedback on the preliminary draft of its report. These activities are summarized here.

Schedule—The MASWG charter was provided to the committee co-chairs, along with formal direction to proceed, in August 2019. Committee candidates were identified and their participation solicited. A planning meeting was held on October 21–23, 2019, at which preliminary topics to be developed were discussed and plans for the committee were developed. The first formal in-person meeting was held on January 28–30, 2020. Additional in-person meetings were planned (and scheduled) but had to be switched to virtual meetings due to the COVID-19 pandemic. Two virtual meetings of the entire committee were held April 20–22 and May 14–15, 2020. Additional shorter meetings of the whole committee and splinter meetings of sub-groups of the committee were held during this time frame in order to develop and vet ideas for our report. Updates on the status of the committee were presented at meetings of MEPAG on November 13, 2019; February 28, 2020; and April 17, 2020.

Activities—MASWG heard presentations at its in-person and virtual meetings on the status of the NASA Mars program, science goals and objectives for Mars exploration, status of both operational and in-development missions, mission concepts, technology development and capabilities, human-mission development, commercial opportunities, PP, and mission cost exercises. These presentations included updates on those Planetary Mission Concept Studies (relevant to Mars) that were being supported by NASA through a different program.

In addition, MASWG solicited one-page "mission concept" white papers from the community to ensure that we were aware of the full breadth and depth of mission concepts that were being considered for future proposal opportunities. This was especially important in the area of small-spacecraft mission concepts, as the technical capabilities in that area have been evolving dramatically over the last couple of years and new science-mission concepts were being developed to take advantage of them. We received ~55 white papers, covering the entire range of mission classes and science objectives. In order to protect proprietary ideas, the community was promised that these white papers would be held as confidential, and thus not shared outside of MASWG, nor discussed as specific concepts in any public forum; these promises were kept.

Vetting—Preliminary results from the MASWG deliberations were made available for review prior to our preparing the final report. We presented them in PowerPoint form to the Directors of the Planetary Science Division and the Mars Exploration Program at NASA Headquarters, and had a discussion with them about the emerging findings and recommendations. We also presented the same PowerPoint package to a virtual meeting of MEPAG on June 26, 2020. Feedback and input were received through discussion following the presentation and also through written feedback provided through an email site.

In addition, we solicited formal reviews of the PowerPoint package from seven senior members of the Mars community. Together, they included science, engineering, Mars mission, and programmatic backgrounds.

A final briefing to NASA Headquarters, prior to delivery of the text report, was made on October 28.

Input from all corners was considered in putting together this final report. Of course, MASWG takes full responsibility for the contents of the report.

Appendix B Science Contamination Control and Planetary Protection Considerations for the Future Mars Exploration Program

A future Mars Exploration Program as envisioned by MASWG must deal with three major constituencies in any set of policies that address contamination control and the legal framework of Planetary Protection (PP).

First, as befits a program that is grounded in basic science, are the new investigations, instruments, and technologies emerging from the mission arcs described in the MASWG document. Science-driven exploration of former (and potentially still) habitable environments will challenge PP policy and implementation as well as instrument design and cleaning.

The second constituency, which has emerged recently, are the spaceflight entrepreneurs, most notably Elon Musk's Space Exploration Technologies Corp., or SpaceX. While the bulk of the SpaceX business is in LEO and occasional launches of communication satellites to geosynchronous orbit, it is the publicly avowed focus on Mars that distinguishes SpaceX from other entrepreneurial companies.

In our MASWG report, we urge some programmatic experimentation with a Mars version of the lunar CLPS program. If such a program were to exist, those commercial providers would be required to address a variety of contamination issues.

Third, human spaceflight to the surface of Mars, an old science fiction concept and an engineering dream that dates at least to the 1948 writings (in German) of Wernher von Braun, brings concerns about contamination to a much greater level. Humans carry billions of microbes, and space suits invariably leak. Thus, any humans landing on Mars must exercise great care in where they go, especially to any areas thought to be habitable or to have been habitable.

As stated earlier, the core concern is contamination by and amongst all three groups that may affect future scientific investigations and possible back contamination of the Earth's biosphere. These concerns were codified in the Outer Space Treaty of 1967 and have been interpreted and applied by NASA and the Committee on Space Research (COSPAR) for more than 50 years. In brief, PP policy and practice address viable organisms. Scientific investigations are concerned about confounding issues in a given measurement, e.g., organic contaminants giving false readings in a highly sensitive spectrometer.

While PP policy and implementation have evolved over the years, there has been growing concern that NASA practice may have fallen behind current developments in biology and not kept pace with the entrepreneurs and new plans for human exploration. To update current NASA policies, there have been three PP studies conducted within the past three years:

- NASEM 2018, Planetary Protection Policy Development Process (P3D)
- NASA Planetary Protection Independent Review Board (PPIRB) 2019
- NASEM 2020, comparison of P3D 2018 and PPIRB

Many issues were raised by the three studies, and for a complete understanding, one should consult the original documents. However, for the purposes of MASWG, a few areas stand out as being worthy of special attention:

In the PPIRB document, it was suggested that certain missions to parts of Mars might be recategorized as so-called Category II, where only minimal reporting and an organic inventory is required. Currently, missions to Mars, even orbiters, are categorized at least as Category III, which carries with it the obligation for substantial documentation, cleaning, and trajectory analysis. Missions that seek to land on Mars are typically Category IV, and a sample return project is labeled Category V. Those latter categories require even more rigorous attention.

The proposed recategorization of Mars missions was motivated in large part by commercial providers who quite understandably would like to develop landing sites with minimum requirements for cleaning and documentation. However, given that the MASWG mission arcs might include subsurface exploration and probing habitable areas, such a relaxation of scientific contamination or PP controls would require substantial study of the mission and its objectives before approval. In addition, as with human exploration, there would need to be a thorough examination of the operational approach before any change in categories. One such proposal is to establish exploration/landing zones that could be sufficiently remote from high-science value sites so that contamination is very unlikely. Research on this topic is immature and requires substantial further effort.

A key element of our MASWG recommendation is to incorporate small spacecraft into Mars exploration at the low-cost end of the spectrum. In the PPIRB report, it was alleged that small spacecraft face undue PP cost challenges. The NASEM 2020 report considered that assertion and found some factual basis. For example, small organizations may not be able to afford the trajectory analysis that would verify (e.g., whether a flyby would indeed miss Mars). Thus, the NASEM 2020 study suggested that NASA should evaluate whether PP costs are a burden on small spacecraft developers and whether there is a cost floor for that work. The NASEM study also suggested that the NASA Office of Planetary Protection may help support small spacecraft providers with some analysis. Given the importance of this topic, NASA should track this ongoing issue.

As stated in all three reports, PP requires a new independent advisory process. It is critical that Mars science be at the table and that this new advisory process be coupled to any Mars Exploration Program advisory group such as MEPAG or the Planetary Advisory Committee.

Finally, the special science contamination and PP issues raised by humans visiting Mars will require that science and human exploration work together to agree on which efforts (measurements and missions) need to occur *before* humans land on Mars. Among the important topics is whether "exploration zones" can be defined successfully. This requires research on contamination control for both science and PP to be funded and conducted. For back contamination, biologists and physicians need to establish what human testing and quarantine is needed.

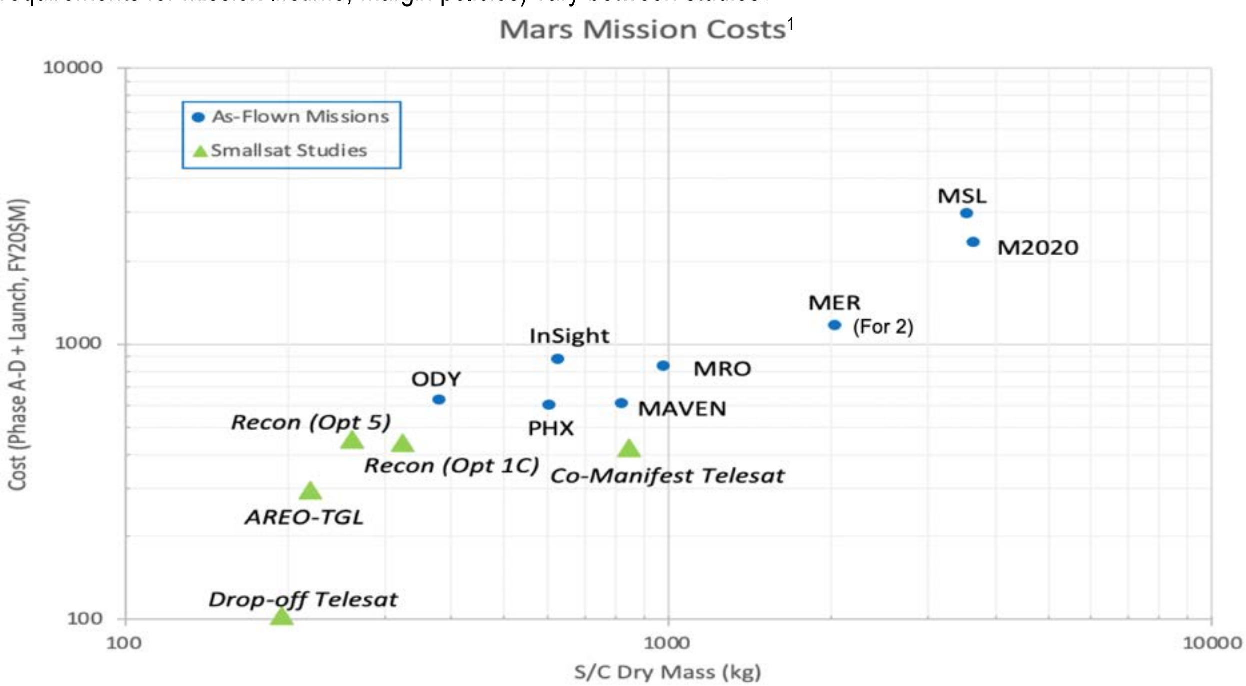
In summary, contamination control for science and new PP issues will need significant ongoing attention.

Appendix C Small-satellite Costs in the Context of Mars Exploration

Small Satellite missions deployed in Earth orbit are providing significant science at lower costs. Their rapid development presents a new opportunity that could dramatically change the cost of doing science at the Moon and in deep space. Small-mission costs have been estimated for a number of candidate missions in Team-X studies at JPL. Including the launch vehicle but not Phase E, these costs are compared to actual mission costs for previously launched Mars missions in Table C-1. With many instruments shrinking in their mass and power needs, payload and spacecraft costs can also be reduced. The candidate cost versus mass studies shown in Table C-1 may not be representative of the full range of possibilities but still illustrates possible trends in a rapidly developing paradigm.

SIMPLEx-class missions are capped at $55M and Planetary Science Deep Space SmallSat Studies looked at mission concepts up to $100M. MASWG felt that these caps were too restrictive for Mars missions, especially because launch vehicle costs were not fully included. The range used in this report for small spacecraft missions was taken to be $100M–300M (Section VI).

Table C-1. Cost Estimates of Small to Large Mission. As-flown missions are compared with studies of small missions conducted by Team-X at JPL (Chad Edwards [JPL], personal communication, May 5, 2020). InSight (NSYT) and MSL costs include impacts of 2-year launch slips. Phase E costs not included. Several factors (e.g., requirements for mission lifetime, margin policies) vary between studies.



[1] *Note: Mission cost assumptions in this document are of a budgetary and planning nature and are intended for informational purposes only. They do not constitute a commitment by NASA.*

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Appendix E Acronym List

3D	Three-dimensional
AO	Announcement of Opportunity
CCP	Commercial Crew Program
CLPS	Commercial Lunar Payload Services
CNSA	China National Space Administration
CoMPS	Commercial Mars Payload Services
COSPAR	Committee on Space Research
COTS	Commercial Orbital Transportation Services
CRISM	(MRO) Compact Reconnaissance Imaging Spectrometer for Mars
CRS	Cargo Resupply Services
CTX	(MRO) Context Camera
DSc	Discovery class
DSN	Deep Space Network
EDL	Entry, Descent, and Landing
EM	Electromagnetic
EMM	(UAE) Emirates Mars Mission
ESA	European Space Agency
EscaPADE	Escape and Plasma Acceleration and Dynamics Explorers
ExoMars	(ESA) Exobiology Mars
FLG	Flagship Class
GEO	Geostationary Orbit
GRAIL	Gravity Recovery and Interior Laboratory
GSFC	Goddard Space Flight Center
Gyr	Billion years
HEOMD	(NASA) Human Exploration and Operations Mission Directorate
HiRISE	(MRO) High-Resolution Imaging Science Experiment
HVM3	High-resolution Volatiles and Minerals Moon Mapper
IDIQ	Indefinite Delivery, Indefinite Quantity
InSight	Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport
ISRO	Indian Space Research Organisation
ISRU	*In Situ* Resource Utilization
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
LEO	Low-Earth Orbit
Ma	Million years (age of materials)
M2020	Mars 2020 mission
MarCO	Mars Cube One
MARSIS	(MEX) Mars Advanced Radar for Subsurface and Ionosphere Sounding
MASWG	Mars Architecture Strategy Working Group
MAV	Mars Ascent Vehicle
MAVEN	Mars Atmosphere and Volatile EvolutioN
MEDA	(M2020) Mars Environmental Dynamics Analyzer
MEP	Mars Exploration Program
MEPAG	Mars Exploration Program Analysis Group

MER	Mars Exploration Rover (*Spirit & Opportunity*)
MEX	(ESA) Mars Express Mission
MGS	Mars Global Surveyor mission
MOC	(MGS) Mars Orbiter Camera
MOXIE	(M2020) Mars Oxygen In-Situ Resource Utilization Experiment
MPIAT	Mars Program Independent Assessment Team
MPO	Mars Program Office
MRO	Mars Reconnaissance Orbiter
MSL	Mars Science Laboratory (*Curiosity*)
MSR	Mars Sample Return
NASA	National Aeronautics and Space Administration
NASEM	National Academies of Science, Engineering, and Medicine
NFc	New-Frontiers class
NID	NASA Interim Directive
NPR	NASA Procedural Requirement
NRA	NASA Research Announcement
NRC	National Research Council
OMEGA	(MEX) Observatoire pour la Mineralogie, l'Eau, les Glaces, et l'Activite
ODY	Mars Odyssey Orbiter
P3D	Planetary Protection Policy Development Process
PHX	Phoenix Lander
PI	Principal Investigator
PLD	Polar Layered Deposits
PP	Planetary Protection
PPIRB	Planetary Protection Independent Review Board
PREFIRE	Polar Radiant Energy in the Far Infrared Experiment
PSDS[3]	Planetary Science Deep Space SmallSat Studies
R&A	Research and Analysis
RFI	Request for Information
RIMFAX	(M2020) Radar Imager for Mars' Subsurface Exploration
ROI	Return on Investment
SAA	Space Act Agreement
SHARAD	(MRO) Shallow Radar experiment
SIMPLEx	Small Innovative Missions for Planetary Exploration
SMD	(NASA) Science Mission Directorate
SpaceX	Space Exploration Technologies Corporation
SSc	Small-Spacecraft Class
SWIM	Subsurface Water Ice Mapping
TES	(MGS) Thermal Emission Spectrometer
TGO	(ESA) Trace Gas Orbiter
THEMIS	(ODY) Thermal Emission Imaging System
UAE SA	United Arab Emirates Space Agency
XUV	Extreme Ultraviolet

Appendix F Acknowledgments

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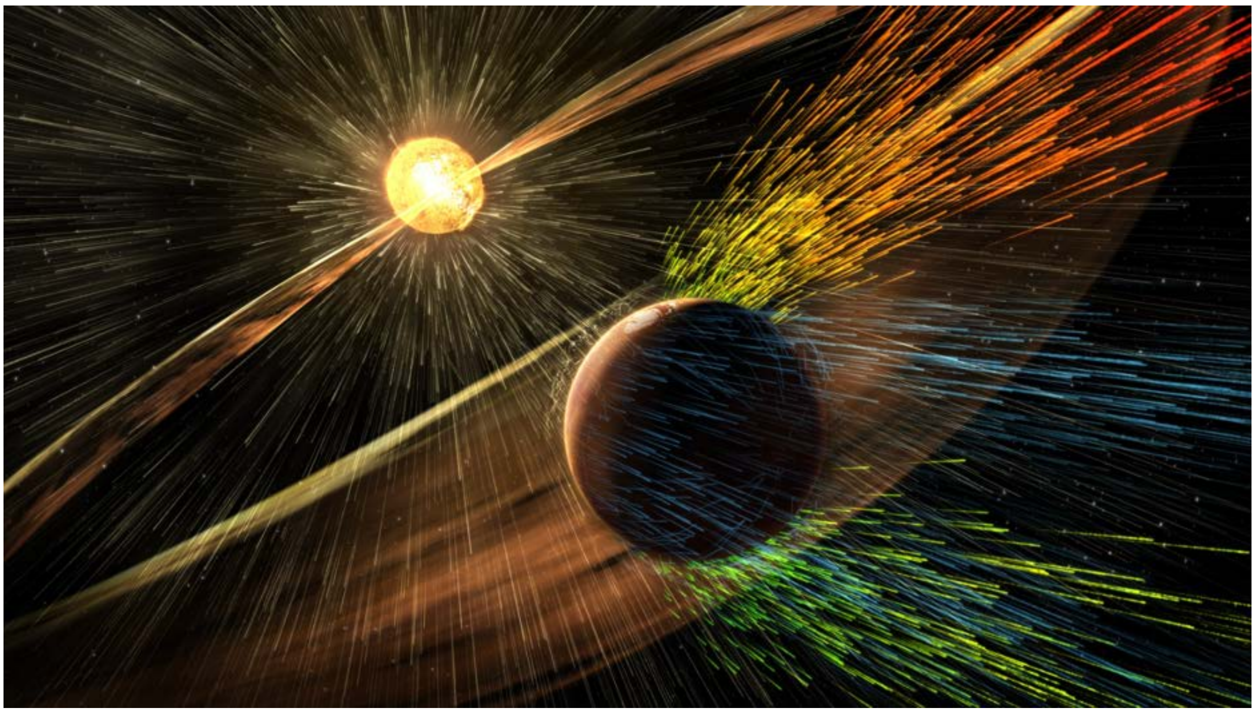

Artist's rendering of a solar storm hitting Mars and stripping ions from the planet's upper atmosphere, based on results from the MAVEN mission.
(Credit: CU/LASP and NASA)